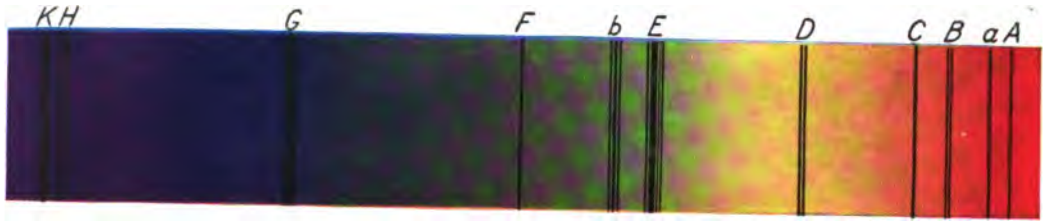

Plate I. Prismatic Spectrum

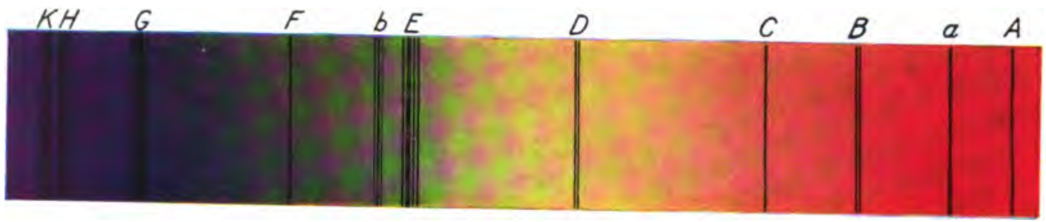

Plate I. Diffraction Grating Spectrum

COLOR

AND ITS APPLICATIONS

BY

M. LUCKIESH, D.Sc.

DIRECTOR LIGHTING RESEARCH LABORATORY NATIONAL LAMP WORKS OF GENERAL ELECTRIC CO.

Author of "Light and Shade and their Applications," "The Language of Color," "Artificial Light, its Influence upon Civilization," "Lighting the Home," "Foundations of the Universe," etc.

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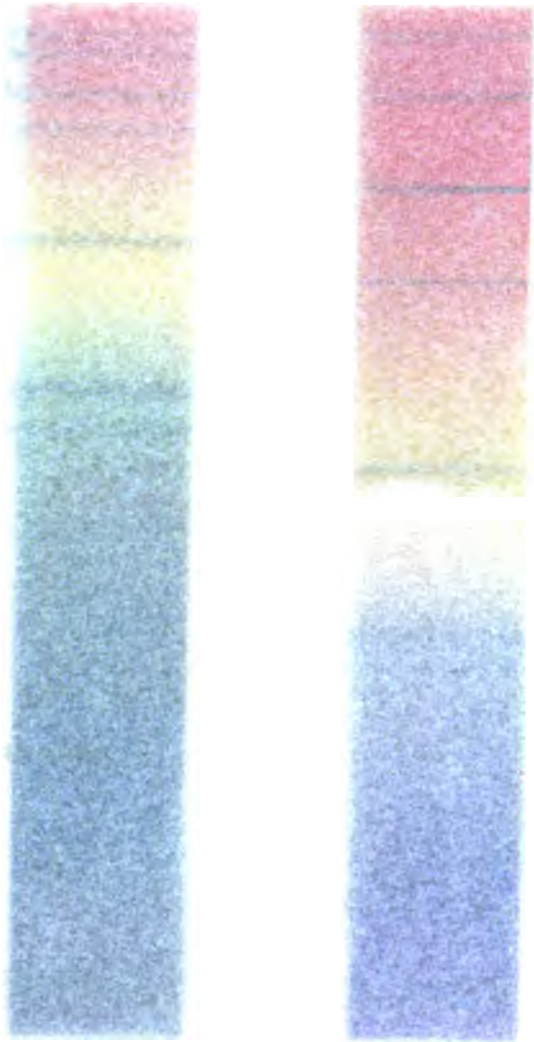

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PRINTED IN THE UNITED STATES OF AMERICA
THE PLIMPTON PRESS, NORWOOD, MASSACHUSETTS

PREFACE

The aim of this book is to present a condensed treatment of the science of color. An attempt has been made to cover as many phases of the subject as possible within the confines of a small volume. During several years of experimental work in the science of color I have been brought into contact with many persons interested in its applications, and the desire has been frequently expressed for a book that treated the science of color as far as possible from the viewpoint of those interested in the many applications of color. These applications are constantly increasing in scope and interest. With this viewpoint in mind I have attempted to treat the subject, exercising my judgment in drawing freely from the work of other investigators in order to make the volume as comprehensive as possible. I do not feel that the work comprises a complete treatment, for there are many interesting phases of color science that have been barely touched upon, and some that have been purposely omitted, because of the danger of straying too far afield. It is believed, however, that this treatise will be helpful to those interested in any of the arts involving the science of color. I have referred to my own investigations quite freely, but trust that this will not be attributed to a lack of perspective. Naturally much of the text involves my own conclusions, but I have aimed to include only those that are supported by experimental data, because only in so far as they are thus supported does

the work become authoritative. Many unsolved problems have arisen throughout the text, which emphasizes the need for more workers in the field. No attempt has been made to present a complete bibliography of even the recent work in this branch of science; but references have been given freely, which, if followed, will provide a substantial beginning to the almost endless chain of material available.

It is a pleasant duty to record my acknowledgments to the management of the National Lamp Works of the General Electric Company, whose broad-minded spirit in establishing the Nela Research Laboratory has made this work possible, and to the director of the laboratory and members of the staff, who always have given freely of their time and counsel.

SECOND EDITION

Some changes have been made in the original text and an extensive chapter has been added. This consists of useful data and methods for their use.

M. LUCKIESH

September, 1920

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CHAPTER I

LIGHT

1. The word Light has acquired two meanings; one pertains to sensation and is therefore physiological and psychological in character, while the other refers to the external cause of the sensation and is therefore physical in nature. As both meanings are used in the study of color, they will be distinguished wherever necessary; for example, light rays when impinging upon the retina of the eye produce the sensation of light. In order to understand the phenomena of color, a fair knowledge of the physical nature of light must first be acquired. Unfortunately the field to be covered in this book is too extensive to permit of a detailed treatment of this interesting subject; only those phenomena will be discussed that are essential to an understanding of the subsequent chapters. Those wishing to pursue this line of study further can readily do so by consulting the many excellent treatises on the subject.

2. *Wave Theory.* — The passage of a beam of light from a source (flame, sun, etc.) to a receiver (the earth, the eye, etc.) involves a transfer of energy, and the question arises as to how this transfer takes place. All around us in Nature, energy is continually being transferred from one place to another and whenever such a transfer does occur *something is moving*. On the ocean, for example, energy is

transferred by water due to its wave motion. Mountain streams are carrying energy, which fortunately can be made to do useful work by means of a water motor, but here the energy is transferred by the onward flow of the water. In air the same two methods of transferring energy are found; currents in the case of winds and waves in the case of sounds. Solids also can be made to transmit energy in these two ways; by currents as in the sand blast and by waves as in the case of sound and other elastic disturbances. Since currents and waves are such common methods of transmitting energy, it is quite natural that they should be called upon to explain the transfer in the case of light. Light travels in straight lines, casts (comparatively) sharp shadows, is reflected from a smooth surface as a regular succession of rubber balls would be if thrown against the same surface, and in many other ways acts much like a current of particles would act if projected from the source of light at a high velocity.

There is one phenomenon, however, that cannot be explained by the assumption of a current of particles; under certain conditions two rays of light of equal intensity can be sent to the same spot in such a manner that the spot will be dark and not twice as bright as it would be if either ray were present alone. This fact is explained by assuming that light energy is transmitted in the form of wave motion for it is seen that if two equal waves are made to pass in the same direction through any medium, but in such a manner that the crests of one wave coincide with the troughs of the other, the two waves will annul each other everywhere, there will be no resultant wave, no transfer of energy, and hence no light at the spot in question. To this phenomenon was given

the name 'interference,' but the term has been extended to include all the phenomena that may take place when two or more waves travel in the same medium at the same time. The foregoing case and all others in which there is destruction of motion are now grouped under the term, destructive interference; in contradistinction to this, there is constructive interference wherever the motion due to all the waves is greater than that due to one. The simplest case of the latter type is that of two equal wave trains traveling in the same direction at the same time but in such a manner that the crests of one coincide with the crests of the other. The two waves reinforce each other and the resultant wave has twice the amplitude of the original waves. Another very important special case of interference is that to which the term 'standing wave' or 'stationary wave' has been applied. This occurs whenever two equal wave trains are passing in opposite directions through the same medium at the same time. The most common way of obtaining equal waves traveling in opposite directions is by means of reflection at a surface perpendicular to the direction in which one train is traveling. Standing waves can be readily demonstrated by fastening one end of a long rope (preferably so that it hangs vertically) and by shaking the other end, timing the motion of the hand so that it is in unison with the reflected waves. It will be seen that some points of the rope remain at rest and others swing through a large amplitude. The points at rest are called nodes and the part of the string between the nodes is a segment. By varying the speed of the hand or the period of vibration the string can be made to vibrate in one, two, three, or more segments.

A brief consideration of wave motion in general

and a few definitions may not be out of place here. In the first place, it is evident that in any wave motion, the parts of the medium do not travel as far as the wave. They remain each in its own region, each causing adjacent parts to move and in so doing gives up to the adjacent part some of its energy. The motion of the particles differ in various kinds of waves. In waves in deep water each drop moves in a vertical plane in a circular orbit. In waves in shallow water the orbit is an elongated ellipse. In media transmitting sound waves the motion of each particle is to and fro in a straight line in the direction in which the wave is traveling. For all waves the *wave-length* is the distance between any two successive particles that are moving through the same points in their orbits at the same instant. The *amplitude* is half a particle's path length (the diameter of the orbit). The *period* is the time taken for the wave to travel one wave-length. The *frequency* is the reciprocal of the period or the number of waves that pass a given point in a unit of time. If two waves are 'in step' so that a crest of one occurs at the same time and place as a crest of the other, the two waves are said to be *in phase*. If a wave is confined to a surface such as that due to a pebble dropped in a quiet pond of water, the waves will be circular; any circle is a *wave front*, and the direction in which the wave is traveling at any point is that of the radius drawn to the point and is therefore perpendicular to the wave front. In the case of light under ideal conditions, the wave will spread out in all directions from a point, so that the wave front will be spherical. The direction of propagation will again be perpendicular to the wave front along the radii of the sphere.

Light energy or radiant energy passes through a vacuum. The phenomenon of interference has been explained by wave motion. Hence it is assumed that there is something in the vacuum that can move. This something is called the ether and is further assumed to penetrate all matter so that light waves always are ether waves; the properties of the waves may change as the matter imbedded in the ether is changed, but it is the ether and not the matter imbedded in the ether that is responsible for the propagation of the light waves. Some scientists, are not reconciled to this view but fortunately in this treatise we need not enter into the discussion.

The adoption of the wave theory necessitates new and somewhat elaborate explanations for such simple phenomena as the rectilinear propagation of light; these have been made by the aid of Huyghen's principle, which states that each point on a wave front may be regarded as a new source of disturbance, sending out spherical waves, and that at any instant the new wave front will be the envelope of all of these secondary wavelets. By the aid of this principle it is at once evident that a light wave in going through a wide slit will pass on in such a manner that the sides of the slit cast a rather sharp shadow, whereas in going through a very narrow slit, comparable in width with a wave-length of light, it will pass on and spread out in all directions thus 'turning a corner.' This phenomenon has been termed diffraction.

It is helpful to visualize light waves by means of the water wave analogy as has been done in the foregoing, but it is well to guard against being misled by following the analogy too closely. For example water waves diminish in amplitude on account of

dissipation of energy through molecular friction. In free space the amplitude of light waves (which is a measure of their intensity) has not been observed to decrease; in other words, there is no friction in the transmitting medium.

3. *Electro-magnetic Theory.*—At first it does not appear that there is any relation between light and electricity, but such a relation was predicted by Maxwell in about 1870. This theory assumes light rays to be identical with the electro-magnetic disturbances which are radiated from a body in which electrical oscillations are taking place. Some years later Hertz actually produced these waves and by this discovery the electro-magnetic theory expounded by Maxwell was supplied with the necessary physical foundation. In enunciating this theory it is customary to state that the oscillating electrons in the atoms which constitute a body send forth through space pulses of electro-magnetic energy. The electron at present is supposed to be *an atom of electricity.* These electric waves emanating from a radiating body whether it be the sun or a red-hot poker have many properties depending upon their wave-length. Although all travel at the same velocity, about 3×10^{10} centimeters (186000 miles) per second, in free space, they differ somewhat in velocity in the ordinary transparent media. In glass, for instance, violet rays travel less rapidly than the red rays. All these rays represent energy and therefore regardless of wave-length have the property of producing heat when absorbed. Sometimes the energy is not wholly converted into heat but enters into chemical reactions or is converted into electricity or radiant energy of other wave-lengths than those of the absorbed rays. Some of the rays, especially those of shorter wave-length than the visible

rays, are very active chemically, affecting a photographic emulsion, destroying bacteria and animal, tissues such as the outer membrane of the eye and causing sunburn; they are also largely responsible for exciting phosphorescence and fluorescence. Other rays have varying effects on organisms and play a more or less important part in the growth of plants. Rays within a certain range of wave-lengths, separately and in groups, produce the sensation of light and color. In other words the retina of the eye can be likened to a receiving station in wireless telegraphy which is 'tuned' to respond to electromagnetic rays of a certain (limited) range of wave-lengths.

4. *Radiation and Light Sensation.*—There are many ways of decomposing radiation into its various component rays. The rainbow is the result of one of Nature's means of dispersing the radiation from the sun into rays of various wave-lengths. The eye sees in the rainbow many colors, the most conspicuous being violet, blue, green, yellow, orange and red. These are seen to be of different brightnesses. If the retina were sensitive to rays of an infinite range of wave-lengths the rainbow would appear much wider than it does. That is, colors whose appearance can not be imagined, would be seen in the now invisible regions beyond the violet and red, because energy corresponding to those wave-lengths is present in sunlight.

The distribution of the energy among the different wave-lengths radiated by a hot solid is shown in Fig. 1. This curve is technically known as a radiation curve and shows that energy of a great range of wave-lengths is present. Such a continuous spectrum is characteristic of the radiation from solid

bodies. On the basis of the electro-magnetic theory of light, it may seem strange that rays of all wave-lengths are produced by the vibrating electrons. This may be pictured sufficiently well for the present purpose by assuming that in a solid body there is considerable damping of the vibrations and that other influences are present which result in the emission

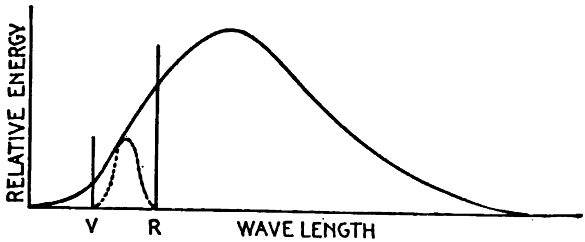

Fig. 1.—Radiation curve of an incandescent solid.

of no characteristic single ray or series of rays but, instead, of rays of all wave-lengths. The height of the curve at any point above the axis of abscissae or base line represents the relative amount of energy of that particular wave-length present in the total radiation. It will be noted that the amounts of energy of various wave-lengths are by no means of the same value. This characteristic of illuminants is of great importance in a study of colors as will become evident later. The region to which the eye is 'tuned,' the visible spectrum, lies between *V* (violet) and *R* (red) which is exaggerated in relative extent for the sake of clearness.

The relation between radiation and light sensation is not simple. The ability of the various rays to produce light sensation is shown roughly by the dotted curve in Fig. 1. The maximum light sensation is produced by rays in the middle of the visible spectrum, namely by those giving rise to a yellow-

green sensation. Beyond the limits of the visible spectrum, *V* and *R*, it is obvious that an infinite amount of electro-magnetic energy causes no sensation of light. The total range of wave-lengths might be called the energy spectrum of this particular radiator. It is obvious that the greater the percentage of the total radiant energy confined to the visible spectrum, the greater is the 'luminous efficiency' of the radiating body. In the production of light the total range of wave-lengths is of interest, but in the consideration of Color, interest is very largely confined to the visible spectrum.

As the temperature of an incandescent body is increased, the energy of the shorter wave-lengths increases more rapidly than the energy of the longer wave-lengths. Considering the visible spectrum, the violet and the adjacent rays increase in intensity more rapidly with increase of temperature than the red and its adjacent rays thus causing the light emitted by an incandescent filament, for instance, to become bluer as its temperature is increased. Here it is well to note that when the various visible rays are permitted to impinge separately upon the retina each produces its own color sensation but when all the visible rays simultaneously stimulate the retina, as in the ordinary viewing of colorless objects, an integral sensation is produced. In the case of most common illuminants the integral sensation is an unsaturated yellow, that is, a yellowish white, while the combined sensations aroused by average daylight produce the integral sensation of *white* light.

In the discussion of Fig. 1 it has been seen that energies in the various wave-lengths differ in light-producing effects. To this must be added the fact that the light-producing effect varies with the inten-

sity. In Fig. 2, *A* represents the light sensation produced in the author's eye by equal amounts of energy of various wave-lengths as measured with a direct comparison or equality-of-brightness photometer. The photometric field was a circle whose diameter sub-

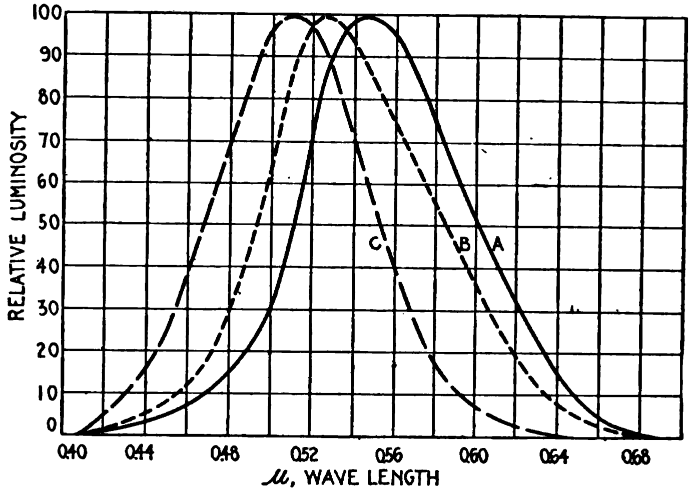

Fig. 2.—Showing the relation between radiant energy and light sensation.

tended an angle of about four degrees at the eye, and whose brightness was equivalent to that of a white surface illuminated to an intensity of 20 meter candles; (a meter candle is the illumination received on a surface everywhere one meter distant from a source of one candle, the surface being perpendicular to the straight line from it to the light source). On decreasing the intensity and therefore the brightness of the photometer field to about one two-hundredth of its original value or to an equivalent of 0.1 meter candle on the foregoing basis, the relation between light and radiation become as shown in curve *B*. It will be noted that the maximum of the luminosity curve (as it is called) has shifted toward the shorter

wave-lengths. In other words at the low illumination the light-producing effect of visible rays of the shorter wave-lengths has not decreased as much as that of the longer wave-lengths. To illustrate by a simple experiment, suppose a red and a blue surface appear of equal brightness at a high illumination. If the intensity of illumination is reduced to a very low value, the blue surface will appear much brighter than the red one. To further complicate matters it is found that even normal eyes differ somewhat in spectral sensibility for experiment shows that the luminosity curves for various normal eyes do not exactly coincide (see # 56). Curve *C* is plotted from Koenig's [1] data obtained at a very low illumination, practically at the threshold of vision. This phenomenon of shifting spectral sensibility which was discovered by Purkinje, and which bears his name, will be discussed in later chapters, and the quantitative relation between radiation and light sensation will be further treated in the chapter on color photometry.

5. *Temperature and Radiation.* — As already stated the effect of raising the temperature of a heated solid body is to increase the luminous efficiency and also the relative amount of energy in the rays of shorter wave-lengths. These effects are shown diagrammatically for a solid body in Fig. 3. The numbers on the curves indicate the absolute black-body temperatures. The wave-length is given in terms of ten-thousandths of a centimeter, this unit being usually expressed by the Greek letter, μ. The rays to which the eye is sensitive lie between *V* and *R*, respectively about 0.4μ and 0.7μ. The eye in reality is sensitive somewhat beyond these wave-lengths but for practical purposes the amount of light sensation produced by rays beyond these limits is usually

negligible. It is seen that as the temperature rises the maximum of the radiation curve shifts toward the shorter wave-lengths. The maximum of the radiation curve of sunlight lies in the visible region. This has brought forth the suggestion that the eye

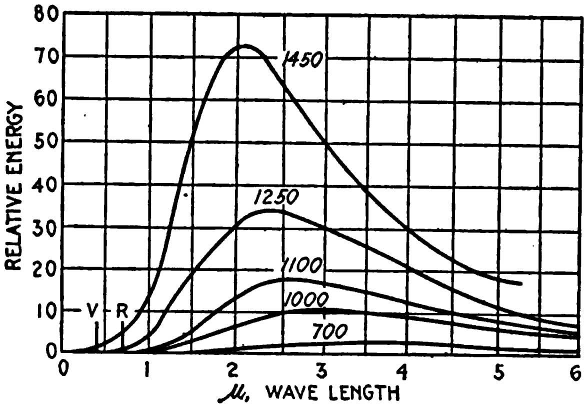

Fig. 3.—Showing the effect of temperature on the radiation from an incandescent solid (black-body).

in its process of evolution has become most sensitive to the rays of such wave-length as are a maximum in the radiation from the sun. As the maximum of the radiation curve shifts toward the shorter wave-lengths, it is seen that a relatively greater proportion of the total energy is found in the visible region between *V* and *R* which accounts for the increase in luminous efficiency. One of the tendencies in light production is toward the development of materials and methods which will enable the light source to be operated at higher temperatures in order to appease the ever-present demand for higher luminous efficiencies. It is evident that the ideal light source emitting a continuous spectrum would be one that radiated no energy beyond *V* and *R*. The area under each curve is proportional to the total amount of energy emitted by the radiator at a certain tem-

perature and the ratio of the area under that part of any curve included between V and R is proportional to the energy that can effect the eye. The ratio of the latter area to the former (for the same curve) is called the 'radiant efficiency' of the radiator as a light source. To make the idea of radiant efficiency of practical value it must be combined with the relations between luminous sensation and radiation.

6. *Spectra of Illuminants.*—The spectral distribution of energy in the radiation from different illuminants is of great importance in the consideration of color owing to the fact that the appearance of the colored objects depends upon the spectral character of the illuminant under which they are viewed. The variation in the spectral character of illuminants is due to the temperature and composition of the radiating body and also to the state in which it exists when radiating luminous energy.

A simple means of producing light is that of heating a solid conductor by passing an electric current through it. At first it will emit invisible radiant energy known as infra-red rays. As the temperature is raised it will finally become luminous, at first appearing a dull red. This is evident from an inspection of Fig. 3. If these light rays be studied by means of a spectroscope which disperses the radiation into its component rays, it will be found that deep red rays are the only visible rays present in appreciable amounts. As the temperature is increased the appearance of the body passes from red to orange, then to yellow and so on. If the body were sufficiently refractory to withstand higher temperatures and remain in solid form, at a certain temperature it would appear *white* and with increasing temperature would assume a bluish white appearance.

The latter temperatures have never been reached in the production of artificial light. Notwithstanding the fact that all solids produce a continuous spectrum and obey the general laws mentioned, it does not follow that they all emit the same amounts of light per unit area at equal temperatures. Kirchhoff has shown by the theory of exchanges that the emissive and absorptive powers of all bodies at the same temperature for rays of a particular wave-length are proportional to each other when the radiation is a pure temperature effect. For a particular kind of radiator called a black body or a full radiator, the relation between emission E, the wave-length, λ, and the absolute temperature T, has been deduced theoretically. The black body is defined as a body that will absorb all radiation incident upon it and reflect none. When it radiates it emits in each wave-length more energy than any other body at the same temperature. The nearest approach to such an ideal radiator is a hollow space enclosed by emitting walls of uniform temperature provided with a small opening through which the radiation can escape. The laws deduced theoretically by various investigators do not agree entirely. The one that best fits experimental data is Planck's law given in

$$E_\lambda = C_1\lambda^{-5}\left(e^{\frac{C_2}{\lambda T}} - 1\right)^{-1} \qquad (1)$$

Another law known as the Wien-Paschen law found to hold for the short-wave region of the visible spectrum is shown in equation (2).

$$E_\lambda = C_1\lambda^{-5}\, e^{-\frac{C_2}{\lambda T}} \qquad (2)$$

In the foregoing equations C_1 and c_2 are constants. The values for these differ somewhat as determined by various investigators.

A simple relation between the wave-length of the maximum of the radiation curve and the absolute temperature is derived from (2) and is expressed in equation (3).

$$\lambda_m T = \text{constant} \qquad (3)$$

Another interesting relation known as the Stefan-Boltzmann law connects the total radiation, E, from a unit area of the radiator with the absolute temperature, T, and is expressed in equation (4).

$$E = CT^4 \qquad (4)$$

These laws are of chief importance in the theory of radiation but are given here as a matter of reference.

A gaseous body is found to emit only certain definite rays and the spectrum is said to be a line spectrum. Sometimes the various lines (which are in reality the images of the slit of the spectroscope, (8) are found to be crowded together in such a manner as to give to the spectrum a fluted appearance. Such a spectrum is called a banded or fluted spectrum. A further striking fact is the constancy of the appearance of the spectra emitted by elements in gaseous form. For instance the spectrum of sodium is always recognized by the position of the emitted rays in the spectrum — that is, by their wave-length. The visible spectrum of sodium consists of a double line (0.5890μ and 0.5896μ) and whenever this double line is found in a spectrum it is certain that sodium is present in the radiating substance. This constancy of the spectra of the elements forms the basis of spectrum analysis by means of which traces of elements far too small to be weighed by the most sensitive balance are readily detected. By means of the spectroscope helium was discovered on the sun before it was distinctly isolated

by scientists on earth. The vacuum tube, the arc, the electric spark, and the flame are used in studying the spectra of elements and compounds.

Sometimes both a line and a continuous spectrum are emitted by an illuminant. Such a case is found in the ordinary carbon electric arc. The crater of the arc being an incandescent solid, emits all visible rays while the incandescent gas of the arc between the electrodes emits a line spectrum the appearance of which depends upon the surrounding medium and the composition of the carbons. In Fig. 4 are shown several representative spectra photographed by means of a grating spectrograph on a Cramer spectrum plate which is sensitive in varying degrees to all the visible rays. This particular brand of photographic plate is relatively less sensitive to blue-green rays so that on viewing the spectrograms the energy in this region appears to be less prominent than it really is. It is seen that the two gases, mercury and helium, emit line spectra. The arcs emit both continuous and line spectra, the latter as indicated above being emitted by the vapor in the arc itself. The relative prominence of the line spectra depends upon the relative intensities of the radiation from the arc as compared to that from the solid electrodes. For instance the line spectrum is much more prominent in the yellow flame arc than in the ordinary carbon arc and as is well known the arc vapor contributes a much greater proportion of the light in the former than in the latter illuminant. The line spectrum of a carbon arc is subject to momentary changes both in character and intensity due to impurities and also to irregularities in the amounts of the chemicals with which the carbons are impregnated. The injection of various chemicals into the arc as sug-

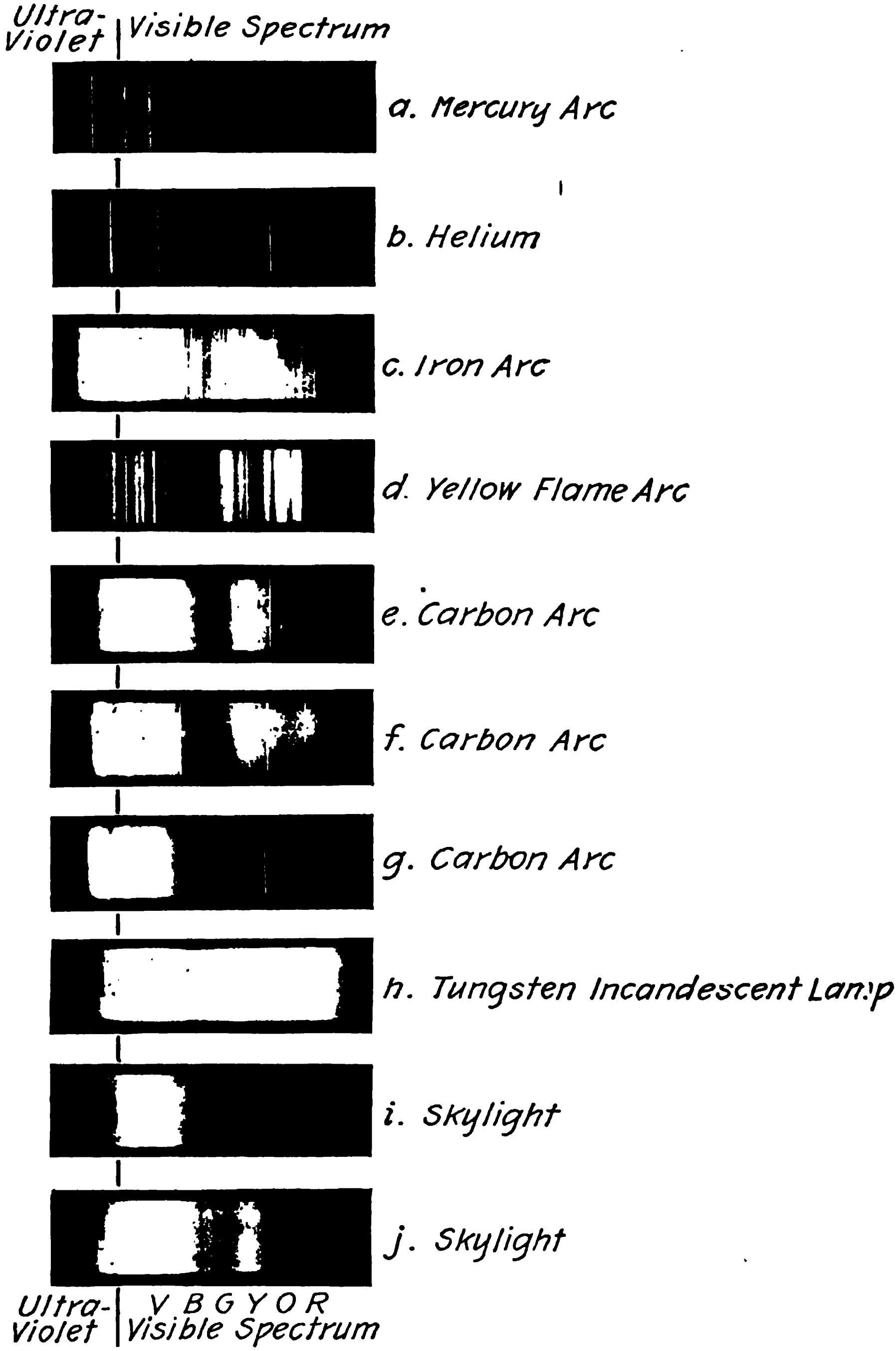

Fig. 4.—Representative spectra.

gested by the heating of metallic salts in a Bunsen flame, affords a means of varying the color or spectral character of the light from the carbon arc lamps. Spectra *f* and *g* were obtained from the same carbon arc within a period of a few seconds. The tungsten filament is seen to emit a continuous spectrum, *h*, the dark band being due to the low sensibility of the photographic plate to blue-green rays. Two spectrograms of light from the sky are shown in *i* and *j* in an effort to bring out the dark lines which cross the spectrum.

The solar spectrum is of special interest. As already indicated a photograph of the spectrum of sunlight made with a narrow slit, shows practically a continuous band crossed by many fine dark lines (see Plate I). These lines were discovered by Wollaston in 1802 but were later studied with better instruments by Fraunhofer in 1814 who found several hundreds of them. These dark lines in the position of various colors show the absence of the corresponding images of the slit of the instrument and therefore the absence of these rays in sunlight. Their absence is attributed to absorption by vapor chiefly in the solar atmosphere. Luminous gases or vapors, as has already been indicated, emit only a limited number of rays, their spectra being discontinuous in appearance. These vapors when luminous are usually opaque to the particular rays which they emit and therefore the light from the sun is robbed of some of the rays in passing through its atmosphere. The Fraunhofer lines are often used as reference points in examining spectra, although electric discharges through gases in vacuum tubes and the heating of salts in a gas flame furnish convenient means of identification or reference spectra in the

experimental laboratory. The chief Fraunhofer lines are given in Table I.

TABLE I

Principal Fraunhofer Lines

Line	Wave-length	Color	Source
A	0.7594μ	Red	Oxygen in atmosphere
a	.7185	"	Water vapor in atmosphere
B	.6867	"	Oxygen in atmosphere
C	.6563	"	Hydrogen, sun
D_1	.5896	Yellow	Sodium, "
D_2	.5890	"	" "
E	.5270	Green	Calcium, "
b_1	.5184	"	Magnesium, "
b_2	.5173	"	" "
b_4	.5168	"	" "
F	.4861	Blue	Hydrogen, "
G	.4308	Violet	Calcium, "
H	.3969	"	" "
K	.3934	"	" "

Other convenient lines obtained by heating salts in a Bunsen flame are — potassium red, 0.7699 and 0.7665 μ; lithium red, 0.6708; sodium yellow, 0.5896 and 0.5890; thallium green, 0.5351; magnesium green, 0.5184; strontium blue, 0.4607. The mercury arc gives a double yellow line, 0.5790 and 0.5764; a bright green line, 0.5461; a faint blue-green line, 0.4916; an intense blue line, 0.4358; and deep violet lines, 0.4078 and 0.4047. Hydrogen at a fairly low pressure in a glass tube through which an electric discharge is passed yields a red line, 0.6563, blue-green, 0.4861, and blue 0.4341. The helium spectrum obtained from a tube such as the foregoing is rich in useful lines throughout the spectrum, yielding red lines 0.7282, 0.7065, 0.6678; yellow 0.5876; green lines 0.5048, 0.5016, 0.4922; blue lines 0.4713,

0.4472, 0.4388; and violet lines 0.4026, 0.3888. Iron, copper, zinc, and cadmium when used as the terminals of an electric spark yield many useful lines, many of which are in the ultra-violet. The iron arc and the quartz mercury arc are particularly useful for exploring the ultra-violet region. Three useful cadmium lines are red 0.6438, green 0.5086, and blue 0.4800.

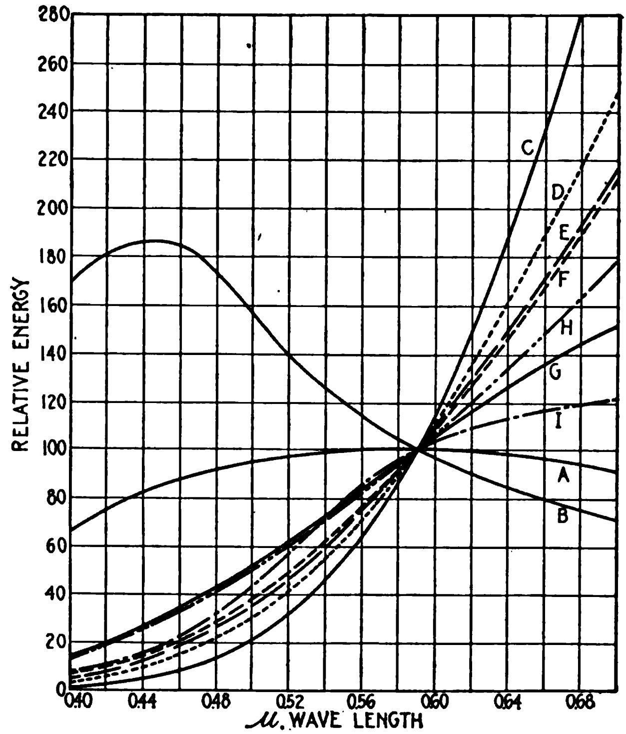

Fig. 5.—Distribution of energy in the visible spectra of various illuminants.

In Fig. 5 and Table II are shown the spectral distributions of energy in the visible region for various illuminants. These data have been obtained in the Nela Research Laboratory chiefly by Hyde,[2] Ives,[3] Cady and the author.[4] As is evident at a glance these

TABLE II

Relative Distribution of Energy in the Visible Spectra of Common Illuminants

	A	B	C	D	E	F	G	H	I
Wave-length	Black body at 5000 deg. absolute (Noon Sunlight)	Blue sky	Hefner lamp	Carbon incandescent lamp 3.1 w.p.m.h.c.	Acetylene	Tungsten (vacuum) incandescent lamp 1.25 w.p.m.h.c. 7.9 lumens per watt	Tungsten (gas) incandescent lamp 0.5 w.p.m.h.c. 22 lumens per watt	D. C. Arc (open)	Welsbach gas mantle
0.41μ	72.	177.	1.9	4.	5.5	....	16.5	....	.....
.43	79.	185.	3.5	7.	9.6	....	22.5	21.8	.....
.45	84.3	187.	6.	12.	15.	16.7	30.	29.	17.5
.47	91.	180.	10.5	18.	21.9	23.5	38.	37.	26.4
.49	92.5	162.	16.3	25.5	30.3	32.7	47.	45.5	38.3
.51	96.	146.	25.5	34.5	40.	42.6	56.5	55.	51.
.53	98.	132.	37.5	47.	52.	54.9	67.	65.5	64.
.55	99.	120.	53.2	62.	66.5	68.6	78.	76.	78.
.57	100.	108.	74.5	79.	82.	83.4	88.	88.	90.
.59	100.	100.	100.	100.	100.	100.	100.	100.	100.
.61	100.	93.	130.	123.	118.	117.	111.	113.5	107.
.63	98.5	87.	168.	148.	139.	136.	121.5	127.	111.
.65	97.1	82.	210.	176.	160.	157.	131.	142.	114.
.67	95.5	77.	260.	204.	182.	179.	140.	156.	119.
.69	93.5	72.5	320.	234.	205.	202.	147.5	170.	120.

curves are plotted in such a manner that the relative energy of wave-length 0.59 μ equals 100. This method of plotting gives the relative distribution of energy for approximately the same amounts of total light sensation. Reference to the spectral distribution of energy in the radiation from the two tungsten lamps, operating at 7.9 and 22 lumens per watt respectively, shows the effect of increasing temperature upon the relative amounts of rays of shorter wave-length emitted. See Table XXIII.

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CHAPTER II

THE PRODUCTION OF COLOR

7. Colors and color phenomena are encountered in nearly every human activity. In fact they are so ever-present that they have become common-place to the average man excepting in those instances where they enter actively into his work. That there is an explanation for every case of color production is inevitable, however, there are some color phenomena as yet unexplained satisfactorily. Color is produced in many ways. It is intimately associated with light as has already been seen. When color is produced it is usually the result either of a subtraction of some of the visible rays from the total radiation emitted by light source or of the dispersion of the visible radiation into its component parts.

8. *Refraction.*— Sir Isaac Newton in 1666 discovered that sunlight consisted of many rays each of which when permitted to impinge separately upon the retina produced the sensation of a distinct color. He accomplished this by prismatic dispersion and proved that no further change resulted from subsequent dispersion.

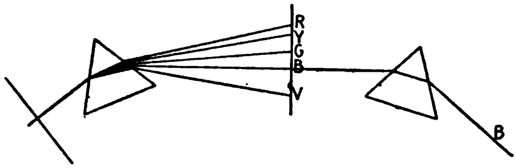

Fig. 6.— Newton's experiment.

Newton's experiment, which is shown diagrammatically in Fig. 6, was performed approximately in the following manner. A prism was set up in a

darkened room and sunlight admitted through a small hole in the window shade. This provided him with a parallel beam of light. After the beam traversed the prism he found that there was no longer an image of the sun, but a colored band similar to the rainbow, made up in reality of an infinite number of colored images of the slit overlapping each other. On passing a narrow portion of this colored band through a hole in another screen and permitting this to traverse another prism, he found no further change in color, thus proving that monochromatic light can not be further decomposed. The principles involved in this experiment are used today in a great deal of spectroscopic work.

Let us examine some of the characteristics of the spectrum somewhat more in detail. It will be found that an increase in the width of the slit produces an increase in the brightness of the spectrum but owing to the facts that the spectrum consists of overlapping images of the slit and that each image of a broad slit is wider than an image of a narrow slit, it is evident that there will be more overlapping of the images produced with a wide slit. The smaller the amount of overlapping the *purer* the spectrum will be. The difference in the appearance of the spectrum of a mercury arc due to a change from a narrow rectangular slit to a wide circular opening is shown in Fig. 7; both spectra were photographed on the same grating spectrograph. The material of which a prism is made also has a marked effect on the appearance of the spectrum. When a ray of light passes through a prism it is

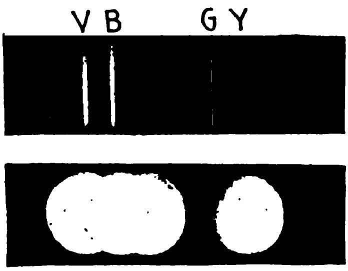

Fig. 7.—Effect of the character of the slit of a spectrograph on the grating spectrum of the mercury arc.

of course bent out of its original direction, the amount of bending or the angle of deviation depending upon the angle of the prism and the index of refraction for the particular wave-length of which the ray consists. If for a given prism the angle of deviation remained the same while the wave-length of the light was changed, then the index of refraction would also remain constant, and if wave-lengths were plotted against either

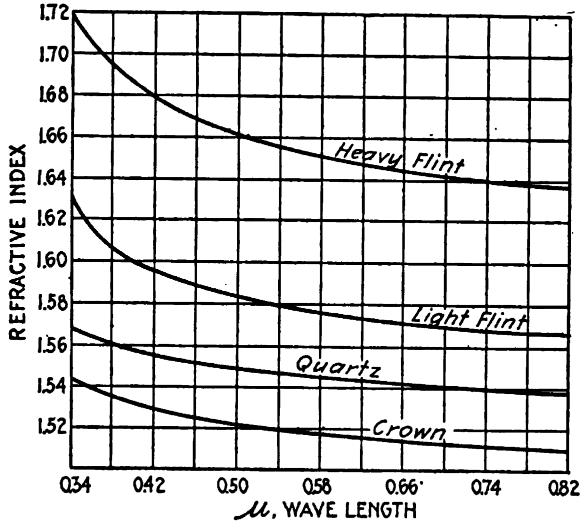

Fig. 8.—Dispersion curves of various optical media.

angles of deviation or indices of refraction the *dispersion curve* would be a straight line. If such a substance actually existed, it would be possible to determine wave-lengths in its spectrum by the use of an ordinary graduated scale. However, such is not the case and further, the dispersion curves of various prisms differ considerably. The dispersion curves of quartz and three kinds of glass are presented in Fig. 8. It is evident from an inspection of these curves that the different wave-lengths are more closely crowded together in the red or long wave-length end of the

spectrum than in the other. This is shown in Plate I (Frontispiece) where a prismatic spectrum is compared with a normal (grating) spectrum in which equal distances represent equal wave-length intervals.

For the study of the visible rays transparent glass prisms are satisfactory but for the study of the invisible rays other media must be used because glass is not sufficiently transparent for very short or very long waves. Hence investigations of the ultra-violet region are made with optical systems of quartz and those of the infra-red with fluorite or rock salt. Extremely long waves such as are used in wireless telegraphy are studied by means of huge prisms of pitch or paraffin.

9. *Diffraction.* — Another common device employed in optical instruments for decomposing visible radiation into its components is the so-called diffraction grating. A grating is simple in appearance but is difficult to make for it consists of a great many parallel lines (sometimes as many as 40,000 and more per inch) scratched usually upon glass or speculum metal. When a grating is placed in the path of a beam of light a spectrum results, which, unlike a prismatic spectrum, has a constant dispersion and is therefore called a normal spectrum.

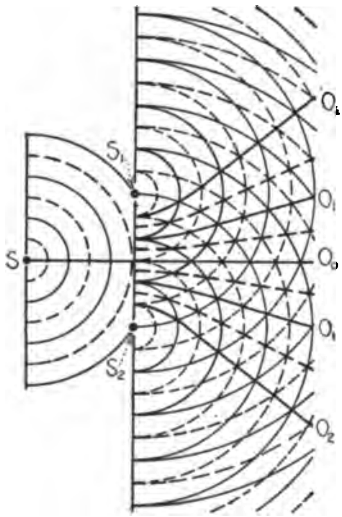

Fig. 9. — Young's double-slit experiment illustrating the principle of the diffraction grating.

To explain the action of the diffraction grating we shall consider only two of the very large number of slits of which the grating consists. In Fig. 9 has been sketched an

instantaneous view of a section perpendicular to the two slits. A source of light, S, has sent out spherical monochromatic waves, successive fronts being represented by the full lines. The dotted lines drawn midway between the full lines must then represent parts of the disturbance exactly in opposite phase with the wave fronts. If the diagram be considered for a moment as representing a surface of water into which a stone has been dropped at S, then the full lines might represent the crests of the waves and the dotted lines the troughs. One wave front is represented as containing the two slits, S_1 and S_2. It was stated in #2 that according to Huyghen's principle any point on a wave front may be regarded as a center of disturbance. The wave front originally proceeding from S strikes the screen and cannot pass through excepting for the two small parts of this wave front that strikes the openings S_1 and S_2. These set up the two systems of spherical waves represented on the right hand side of the screen. It has also been stated (#2) that, whenever two or more systems of waves travel in the same medium at the same time, interference results. Wherever two wave fronts intersect (two crests in the water analogy) there will be an especially large disturbance; wherever two of the dotted lines intersect there will be an especially large disturbance (an especially deep trough in the water analogy). Where a wave front meets a part of the disturbance in opposite phase, that is wherever a full line intersects a dotted line, there will be destructive interference and consequently no motion. The heavy full lines have been drawn through those points where there is maximum motion and the heavy dotted lines through those points where there is no motion and therefore no light. Now suppose these

waves be permitted to impinge upon a screen represented by the right hand edge of the diagram. There will evidently be light on the screen wherever a heavy dotted line terminates.

Imagine that the source *S* has been sending out blue light and is now exchanged for one that emits red light. A very similar diagram will result but on account of the longer wave-length, the ends of the heavy lines will no longer intersect the screen at the points 0_1 and 0_2; there will still be light at 0_0 as is evident from the symmetry of the diagram, but the new points corresponding to 0_1 and 0_2 will lie somewhat farther from 0_0 than in the case of blue light.

Finally, suppose the source *S* to emit white light (light of all visible wave-lengths). Then there will be a white spot at 0_0 and spectra at 0_1 and 0_2, and the blue edge of these spectra will be nearest 0_0. In other words, in a grating spectrum the long wavelengths are deviated more than the short ones, which is opposite to the condition that exists in prism spectra. Further, it will be seen that the distances in the spectra, 0_1, 0_2, etc., are proportional to the wave-length; in other words, that a grating spectrum is one of constant dispersion. (See Plate I.)

The spectra, 0_1, are said to be of the *first order*, 0_2 of the second order, and so on. It is also evident that if more heavy lines had been drawn in the diagram the positions of the third and higher order spectra would also have been indicated. It will be further noted that the higher the order the greater is the length of the spectrum, and therefore the greater is the dispersion.

The colors of some crystals such as the fiery opal, and of insects and feathers are often accounted for by the phenomenon of diffraction. On looking at

an arc lamp through a screen door or the meshes of an umbrella top, diffraction spectra are seen. Likewise on viewing a light source over a thin edge of an opaque object held close to the eye, a colored fringe is seen. These bands are due to the interference of light waves. Since the wave-length of red light is greater than that of violet light, the red light penetrates further into the shadow than the violet light.

The first gratings were made by Fraunhofer in 1821, and consisted either of fine wire or of fine rulings on a smoked glass. At present gratings are ruled by means of a diamond on glass and on the bright reflecting surface of speculum metal. Rowland at Johns Hopkins University contributed much toward the production of satisfactory gratings. On his machine as high as 110,000 lines per inch can be ruled, but usually the number does not exceed 15,000 or 20,000. Cheap copies of gratings are obtained by flowing a film of celluloid dissolved in amyl acetate over a grating, afterward stripping this off and mounting it between plate glasses. It is evident that in the case of rulings upon an opaque substance such as speculum metal the spectra must be produced by reflection and not by transmission as discussed above. The individual rulings always act as absorbing bodies while the unruled portions either reflect or transmit this light.

10. *Interference.*— Other color phenomena besides that of the diffraction-grating spectrum arise from the process of interference. Thin films of transparent substances such as oil on water, soap bubbles, thin sheets of mica, and iridescent crystals, owe their color usually to the interference of light waves. If a slightly convex glass surface be placed upon a

plane piece of glass, colored bands known as Newton's rings will be seen. These are due to interference between the light waves reflected from the upper and lower surfaces respectively of the thin film of air of varying thickness between the two pieces of glass. When white light is incident normally at the point of contact the colored bands are circular and concentric with the point of contact. These bands are violet on the inside and red on the outside but at a short distance from the center they begin to overlap and gradually disappear. If monochromatic light is used the bands appear of the color of the light and many bands can be seen. In the case of some crystals such as chlorate of potash and fiery opals, the colors are found to be very pure. The colors of insects and feathers are often accounted for by the phenomena of interference. The process of color photography devised by Lippmann (# 57) is based upon the principle of interference of light waves.

11. *Polarization.* — Imagine for the sake of simplicity a beam of sunlight emerging from an aperture in a window shade. All the different waves that make up this beam are traveling in the same general direction. As mentioned previously, light waves are transverse; that is, the particles of the medium that transmit the waves move to and fro in a straight line perpendicular to the direction in which the beam is traveling. In the simplest case all of the particles that transmit a wave move so as always to be in one plane. For example in *a*, Fig. 10, the particles *A*, *B*, *C*, *D*, etc., move to and fro along perpendicular paths but the wave travels horizontally. If such a wave could be seen from one end it would appear simply as a short straight vertical line as indicated in *b*. Suppose that the beam of sunlight emerging through

the window shade could be examined minutely end on. We would then see something similar to *c* for the different waves vibrate in all possible different planes. Suppose further that by some means the beam could be transformed so that when seen end on, it would

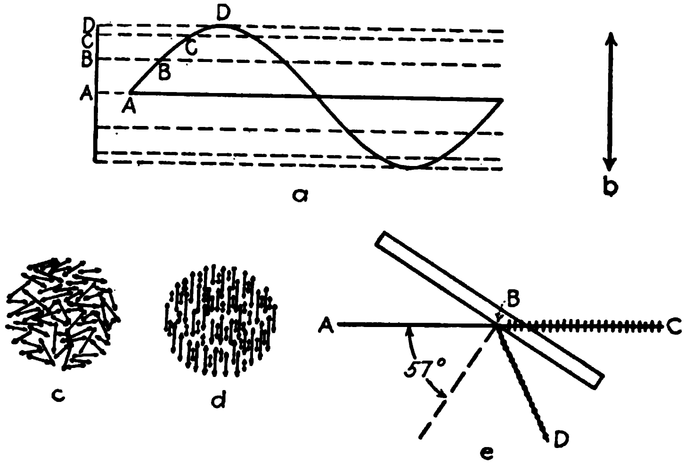

Fig. 10.—Diagrammatic illustration of polarized light.

appear like *d*. Such a beam consisting of waves in parallel planes is said to be a plane-polarized beam, and curiously, the nomenclature adopted states that such a beam in which the waves all move in vertical planes, is *polarized in the horizontal plane*. It is understood that these graphical diagrams are used for the sake of presenting the subject pictorially and with no claim that they represent actual conditions. Nevertheless if the actual conditions were such the results of experiments would readily be explained by the reasoning used here. One simple way of 'polarizing' a beam of light is by permitting it to fall upon a plate of glass so that the angle of incidence is 57 degrees as shown in *e*. The unpolarized beam *AB* will be separated into refracted (*BC*)

and the reflected (*BD*) beams, and the former will be found to consist mainly of waves vibrating in the plane of the paper, as indicated by the cross lines representing the path of the particles, while the reflected beam will be found to consist of waves vibrating perpendicular to the plane of the paper as indicated by the dots representing the paths seen end on. To show that the beam *BD* really has different properties than *BC* it is only necessary to attempt to reflect each from another piece of glass. If the second piece of glass be placed at *C* in a position similar to the first, the beam *BC* will pass through but if it be rotated about *C* through an angle of 90 degrees keeping its angle with the beam constant it will be found that the beam *BC* will not be transmitted. The treatment for the beam *BD* is obvious.

Another means of polarizing a beam of light is by permitting it to pass through certain crystals, such as tourmaline, Iceland spar and quartz. If this be done it will be found that the incident beam is divided into two beams polarized at right angles to each other, the two having different directions in the crystal, different velocities and different properties in general. One of these beams will always be found to obey the ordinary laws of refraction, for example, that the incident ray, the normal to the surface, and the refracted ray all lie in one plane; the other beam will not obey the foregoing and other simple laws generally. The former is therefore called the ordinary ray and the latter the extraordinary ray. Nicol devised a very convenient method of separating the two beams when produced by a crystal of Iceland spar as illustrated in Fig. 11. If a rhomb of spar be cut into two parts along the plane

indicated by the diagonal, *PP*, and if the parts be polished and cemented together with Canada balsam, the paths of the two beams will be as indicated. The Canada balsam has a refractive index intermediate between that of the spar for the ordinary and extraordinary rays. Therefore the ordinary ray, *O*, being incident upon the balsam layer at an angle greater than the critical angle, is totally reflected while the extraordinary ray is merely slightly refracted by the layer of balsam.

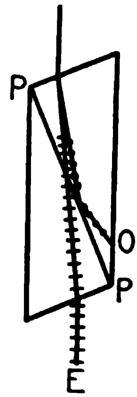

Fig. 11.—The Nicol prism for obtaining plane-polarized light.

That the beam emerging from the Nicol prism is really plane-polarized can be shown by a mirror, as before, or more simply, by a second Nicol prism. If the second prism be rotated through one complete revolution, two positions will be found for which the light transmitted by both prisms is practically of the same intensity as that transmitted by one, and two other positions will be found for which no light is transmitted. For intermediate positions the intensity of the light will be less than that transmitted by one Nicol. When the maximum amount of light is transmitted the Nicols are said to be 'parallel' and when no light is transmitted they are 'crossed.'

Some substances, such as quartz (cut in a certain manner), sulphate of lime, sugar solution, and turpentine, behave in a peculiar manner when placed between crossed Nicols, for though no light passes the second prism before the introduction of the other substance, some light is transmitted when the substance is inserted in the path. If monochromatic light is used the light can be extinguished by rotating either prism to the right or left by an amount depend-

ing upon the substance, its state of concentration if in solution, and the thickness of the layer introduced. Such layers are said to rotate the plane of polarization. If various monochromatic lights of different colors are used in succession it will be found that the prism must be rotated different amounts for the different colors in order to bring about a total extinction of light after the introduction of one of the substances. Hence if such a substance be examined in white light, a certain position of the prism will extinguish the blue light but permitting the remaining colored rays to pass in varying proportions; at another position yellow will be extinguished and the remaining rays permitted to pass in varying proportions, and so on. The transmitted light will of course have a different color in each case. As quartz is one of the chief substances having this property, the following table is given to show the magnitude of the rotation in degrees produced by two thicknesses of quartz for light of different wavelengths.

Thickness of quartz	Red	Orange	Yellow	Green	Blue	Violet
1 mm.	18°	22°	24°	30°	32°	42°
7.5 mm.	135	161	180	218	232	315

Another instance of the production of color by polarization is that of the examination between crossed Nicols of certain other crystals that transform plane-polarized light into so-called circularly or elliptically-polarized light. Many minerals occuring in Nature have either this property or that of rotating the plane of polarization, and an entire system has been developed for determining what substances are

present in a given rock by noting the color effects produced by a thin section of the rock in a microscope equipped with two Nicol prisms.

12. *Reflection, Absorption, Transmission.*—Ordinary colors, which are encountered, are produced by selective reflection or transmission. Since most substances do not have the property of reflecting the same proportions of all light rays received they are said to be selective in their reflection. A red fabric has the ability to reflect chiefly the red rays of the visible spectrum; therefore when white light falls upon it only the red rays are reflected while the remaining visible rays are absorbed. By this process of selective reflection the colors of pigments and most of the colors in Nature are produced. The same remarks apply to the production of color by selective transmission. Colors produced by these means are not as pure as the colors of the spectrum. Each of the latter consists practically of a single wave-length and are said to be monochromatic, while the colors ordinarily encountered in Nature are impure, consisting of rays of a considerable range of wave-lengths.

In Fig. 12 are shown diagrammatically the spectral analyses of five common pigments. For each pigment the reflecting power (i.e. the per cent of energy reflected) was determined for all wave-lengths in the visible spectrum. The results plotted against the corresponding wave-lengths are represented by the full lines in the diagram. The dotted curves represent roughly the relative light values and are obtained from the full curves by multiplying the energy values represented by the ordinates by their relative abilities to produce light sensation (#4). A similar discussion applies to the same colors pro-

duced by transmission. These analyses will be discussed further in Chapter V. (See Figs. 122 and 123.)

The character of the surface of a pigment and the density of the coloring matter influence the appearance of a color. If, for instance, a red aniline dye solution be deposited upon a fabric by means of an air brush, the pigment under some conditions will

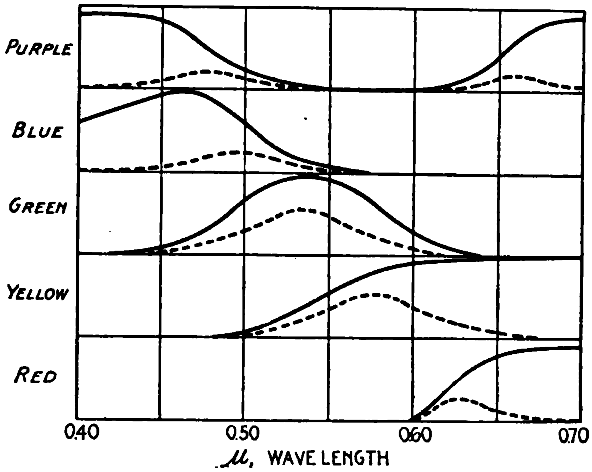

Fig. 12.—Analyses of ordinary colors.

be deposited in the form of a fluffy powder whose appearance is a deep velvety red. The purity of the red is largely due to multiple reflections, for the light is able to penetrate an appreciable distance into the medium (# 64, 75), and at each reflection it becomes purer—that is, more nearly monochromatic. If the solution were applied by means of an ordinary brush, the deposit would not have been so porous and the appearance of the color would not have been such a deep red. Another instance of the effect of multiple reflections on the color of light is found in a gold-lined goblet. All are familiar with the color of gold plating. This, however, becomes much more

reddish when inside a goblet, owing to the purifying effect of multiple reflections.

The color of transparent media depends upon the depth of the coloring matter. For instance, a hollow glass wedge, when filled with an aqueous solution of ethyl or methyl violet, will appear bluish at the thin end and reddish at the thick end. Cyanine is another dye that exhibits dichroism, which is the name applied to the foregoing. The different appearances of silk and woolen fabric dyed in the same solution are due largely to the difference in the character of the surfaces. Many of these instances could be cited here, but the details will be treated in succeeding chapters.

13. *Color Due to Scattered Light.* — That light is changed in color by being scattered by fine particles is a fact observed daily. Tyndall, by precipitating clouds of vapor, observed that as the particles increased in size the bluish color of the clouds disappeared. Smoke from the end of a cigar appears bluish, yet the smoke exhaled appears whitish; this latter is perhaps caused by an increase in the size of the particles, due to the condensation of moisture. Rayleigh [1] has mathematically treated the problem of scattered light and experimented with a sulphur precipitate. He noted a polarizing effect which is of interest. J. J. Thomson [2] treated the scattering due to small metallic spheres theoretically. Garnett [3] concluded that colored glasses owe their colors to the presence of microscopic spheres of the metal of the coloring agent. Colloidal solutions appear to act in the same manner. Mie [4] has extended Garnett's theory very considerably; however, the exact explanation of the color of glasses is still somewhat disputed.

The color of daylight is of special interest because

it is our most common illuminant. Light from the sky consists chiefly of scattered sunlight in daytime. If it were not for the finely divided particles of matter in our atmosphere, the sky would be quite as dark by day as by night. When the particles are of a size comparable with the wave-length of light rays, they produce considerable scattering of the latter. This scattering of light is selective, the rays of short

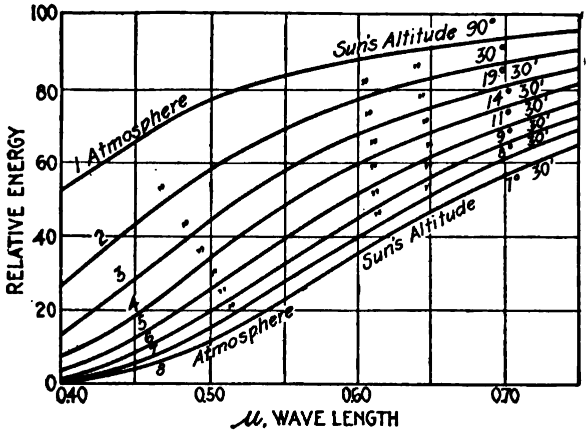

Fig. 13.—Showing the variation in the spectral character of sunlight due to atmospheric absorption.

wave-length being scattered in greater amounts than those of longer wave-length; this accounts for the bluish color of the sky (Fig. 5). Sunlight is termed white light, but in many cases throughout this book the term 'white' light is used to indicate the total light from an illuminant emitting all visible rays. Where necessary, the two meanings are differentiated. Direct sunlight, however, undergoes a change in color as the altitude of the sun changes, on account of the greater thickness of air, more or less laden with smoke, dust, vapor, and ice, through which the light must pass at the lower altitudes. This change in color caused by the combined actions of

absorption and scattering, is such as to depress the blue, and hence the sun appears redder as it approaches the horizon. All the brilliant colors of sunset are due to the foregoing phenomena. The effect of different masses of air upon the relative amounts of energy in each wave-length which reach a given point on the earth's surface has been determined by Abney; his data are reproduced in Fig. 13. Of course the results obtained will depend upon the purity of the atmosphere. Over a smoky industrial city, the sun, when near the horizon, almost daily appears a fiery red. Often the absorption is so great that the sun disappears from view long before it actually sinks below the horizon.

14. *Color Sensations Produced by Colorless Stimuli.* — Colors are often visible to a careful observer when not produced by any of the methods already mentioned. If a disk composed of black and white be rotated at the proper rate — moderately slow — colors appear upon the leading and lagging edges of the sectors.

In other words when the black and white stimuli precede or follow each other at certain intervals, colors are produced instead of gray. Fechner, in 1838, was perhaps the first to describe these subjective colors, and his name was later applied to the phenomenon by Brücke. Many have studied the problem and there is a general agreement as to the results obtained, though there is no such agreement

Fig. 14.—Benham disk for producing subjective colors by means of black and white stimuli.

as to their explanation. Benham,[5] in 1894, produced a disk different from those used by preceding investigators and made an attempt to solve the problem. One form of his disk, illustrated in Fig. 14, shows the colors in a striking manner when rotated. The phenomena can only be briefly discussed here. In general, when black is followed by white at a moderate speed, a sensation of red results, but if white be followed by black, a sensation of blue is experienced. By introducing various angular intervals, as is done in the Benham disk, sensations of intermediate colors are aroused. On rotating the disk in one direction the blue sensation is aroused in the inner ring and red in the outer; on reversing the disk, the colors aroused are also reversed in their order. The phenomena are interesting and have received a great deal of attention, though, as already stated, there is no general agreement as to their complete explanation. No doubt retinal inertia and the difference in the rates of growth and decay of the color sensations are important factors in the production of these so-called subjective colors. Often, when suddenly moving the eye over black and white surfaces in the field of vision, these colored effects are perceptible. A simple disk for showing the Fechner colors, though not as effective as the Benham disk, is one containing plain black and white sectors. On rotating such a disk at a certain speed it will appear of a greenish hue, but at a somewhat more rapid rate of rotation it appears a reddish hue. Helmholtz used a white disk upon which was painted a black spiral. Rood[6] used an opaque disk with four open sectors, each of seven degrees. Through this rotating disk he viewed a clouded sky. With a rate of nine revolutions per second the sky appeared a

deep crimson hue, except for a small spot in the center of the visual field, which remained constantly yellow. This latter is probably due to retinal differences. The center of the retina, called the 'yellow spot,' is known to exhibit selective absorption. At eleven and one-half revolutions per second the field appeared bluish-green.

15. *Fluorescence and Phosphorescence.* — Usually the radiant energy absorbed by bodies is transformed into heat energy. There are many substances, however,—some solid, some liquid, and some gaseous,—that have the property of absorbing radiant energy of certain wave-lengths and of emitting it again after transforming it into radiant energy of other wave-lengths (nearly always longer than those absorbed).

The name fluorescence was derived from fluor spar (calcium fluoride), which has long been known to possess the property of emitting light rays of a different color than that of the rays with which it is illuminated. Strictly speaking, the term applies to the phenomenon only when it ceases immediately after the exciting light is extinguished; in this sense it is applicable to liquids and gases only. In solids the phenomenon usually continues for some time after the exciting light has been shut off. This prolonged emission, which in some cases lasts for hours, is termed phosphorescence. The phenomena of fluorescence and phosphorescence are sometimes classified under the more general term luminescence. Though there are comparatively few substances that exhibit the phenomenon to a marked degree, it is difficult to find materials that do not show the property slightly. This is readily seen by examining ordinary substances in an intense spectrum of the

light from a quartz mercury arc produced by means of a quartz optical system. In examining the fluorescent light it is often convenient to look through a glass of such a color that it will transmit the fluorescent light rays and absorb the exciting rays. The phenomenon is influenced by temperature, and in most cases the phosphorescence is temporarily increased in brightness by the application of heat or red and infrared rays, but the duration of this increased brightness is usually brief, as the phosphorescence is rapidly extinguished by these agencies. The phenomenon is of great interest to the scientist and also in smaller degree to the colorist and light-producer. Fluorescent phenomena play a part in the appearance of certain colors (# 75), and there are possibilities for utilizing the phenomenon for the production of light for practical purposes.

Some examples of fluorescence and phosphorescence should be of interest. Sunlight and the light from carbon, mercury, zinc, iron, and silicon arcs are rich in ultra-violet rays which ordinarily are the most active in exciting fluorescence and phosphorescence. In these cases it is convenient to remove most of the yellow, orange, red and infrared rays from the exciting beam by means of a dense violet glass and a water cell. Uviol blue glass is especially satisfactory. Water of a few centimeters depth is practically opaque to infrared rays, but when pure is quite transparent to ultra-violet rays. The fluorescence, consisting in general of rays of longer wave-length than the exciting light, can be viewed through a glass of proper color without being confused by the color of the exciting light. Fluorescent materials are valuable in visually investigating the ultra-violet region of a spectrum; for example, uranium glass is very

convenient for focussing a spectrograph for the invisible ultra-violet rays.

Aesculine, which is ordinarily transparent in solution or in a gelatine film, fluoresces a bluish color under strong ultra-violet excitation. It is valuable in photography as a screen for absorbing ultra-violet rays. A solution of fluorescein or uranin is useful in demonstrating the path of light through various optical systems. It is best to prepare first a solution of moderate concentration and add this drop by drop to the tank of clear water. Of course the difference between the refractive index of the water and that of air must be taken into consideration when demonstrating the path of light through a given optical system immersed in water. Kerosene, an alcoholic solution of chlorophyl, anthracene, and many of the organic dyes exhibit the phenomenon of fluorescence. In cases of strong excitation the emission of light rays by some of these substances continues for some time after the exciting light is cut off.

Substances that exhibit prolonged phosphorescence are chiefly the alkaline earth sulphides. Balmain's paint, an impure sulphide of calcium, is one of the most active and least expensive. Its phosphorescent light is of a bluish color. Other phosphorescent sulphides emit light of various colors, and by combining various ones, nearly any desirable color can be obtained. For demonstration purposes beautiful designs can be made by the use of various phosphorescent media which emit light of different colors. The chief difficulties which limit the use of phosphorescent substances are the scarcity of the exciting rays in ordinary light sources and the rapid decay of the intensity of the emitted light after the excitation has been cut off.

One instance of a commercial application of fluorescence as a light source is the adaptation of a rhodamine reflector to the mercury vapor arc lamps by Peter Cooper Hewitt. The reflector consists of a white paper base upon which the rhodamine layer is placed. The latter is apparently protected by a transparent varnish. On focussing the spectrum from the quartz mercury arc upon it and viewing it through a red glass, it is seen that practically all rays from green to the extreme ultra-violet excite the red fluor-

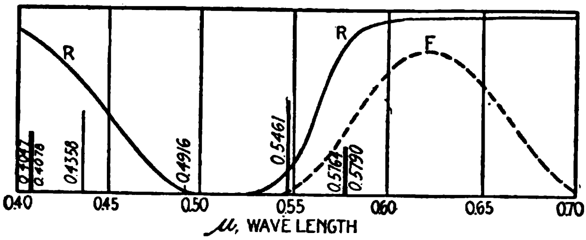

Fig. 15.—Diagrammatic illustration of the action of the rhodamine fluorescent reflector.

escence. That is, a photograph through a red filter of this projected spectrum appears quite the same as an actual spectrogram of the light from the quartz mercury arc. The action of the reflector is diagrammatically shown in Fig. 15. The heavy vertical lines represent the visible lines of the mercury spectrum, their lengths being approximately proportional to their energy intensities; curve *R* represents the reflection curve of the rhodamine dye, and *F* the fluorescent light. It is seen that a gap in the spectrum of the light from a mercury arc equipped with this reflector exists in the blue-green region. While this reflector greatly improves the appearance of colored objects illuminated by the mercury arc, the light is still unsatisfactory for accurate color work, owing to the gap mentioned and to the strong emission

lines. In Fig. 16 is given the spectrophotographic analysis, by means of a prism instrument, of the properties of the rhodamine reflector. The slit of the spectrograph was purposely adjusted somewhat wider than usual, on account of the long exposure (several hours) required to obtain a spectrogram of the fluorescent light. *a* represents the reflection of the reflector for tungsten light; *b*, the spectrum of the tungsten light; *c*, the mercury spectrum; *d*, the reflection of the rhodamine reflector illuminated by the total light from the mercury arc; *e*, the mercury spectrum (shorter exposure); *f*, the isolated mercury green line produced by a special filter described later; *g*, the fluorescence spectrum excited by the green line, the latter also appearing owing to diffuse reflection from the fluorescent reflector. This reflector furnishes red rays to the mercury vapor lamp, when so equipped, at the expense of practically all the other rays. The scheme is an ingenious one, and probably paves the way for other practical uses of the phenomenon of fluorescence.

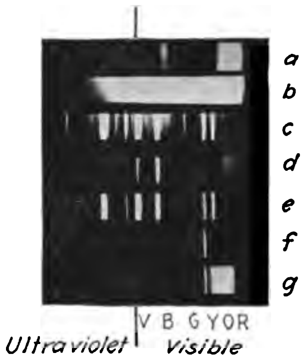

Fig. 16.—Spectrophotographic analysis of the action of the rhodamine fluorescent reflector.

In the study and practical use of fluorescent substances the solvent is of importance, owing to the influence upon the intensity of the fluorescence. Knoblauch[7] investigated the subject, obtaining the results given in Table III. The figures ranging from one to eleven indicate the order of the intensity, eleven being the most intense. The table is also of interest in suggesting a variety of solvents for dyes when these may be unknown to the experimenter.

TABLE III

Effect of Solvent upon the Intensity of Fluorescence

	Water	Glycerine	Methyl alcohol	Ethyl alcohol	Acetone	Isobutyl alcohol	Amyl alcohol	Ethyl ether	Gelatine	Xylol	Toluol	Benzol
Aesculine	3	3	3	3	1	3	2	...	...	...	...	...
Anthracene	...	...	...	4	3	5	4	4	...	5	5	5
B. Phenylnaphthylamin	...	...	5	5	3	5	4	2	...	1	1	1
Chrysaniline	...	...	1	2	...	...	3	...	...	...	...	...
Chrysolin	2	3	3	3	...	3	1	...	...	...	...	...
Eosine (sodium)	1	2	6	5	...	...	4	...	3	...	...	...
Fluorescein (lithium)	2	3	5	4	...	...	1	...	...	...	...	...
Fluorescene	...	...	1	2	...	...	3	...	...	...	...	...
Petroleum	...	...	...	5	4	...	...	3	...	6	6	6
Phenosafranine	1	6	7	9	11	9	10	...	...	4	3	2
Magdala red	...	...	4	4	...	...	3	...	...	...	1	1
Curcumin	...	...	1	2	...	3	4	...	...	...	...	...
Phenanthrene	...	...	...	1	...	...	...	...	...	...	...	2

16. *Useful Filters.* — Very often in the study of color phenomena monochromatic light is desired, or ultra-violet and infrared regions of the spectrum must be isolated. For these reasons various filters which have been found convenient will be described.

For obtaining intense monochromatic light the quartz mercury arc is a valuable source. Filters can be prepared for isolating the various lines. The filters can be made of dyed gelatine and cemented between glass plates (or quartz, if necessary) with Canada balsam, or the dyes can be dissolved in a proper solvent and used in glass or quartz cells. The filters can be tested visually by means of a spectroscope or photographically with a panchromatic plate and a spectrograph.

For isolating the mercury yellow lines, 0.5790 and 0.5764 μ, chrysoidine and eosine are satisfactory.

For isolating the green mercury line, 0.5461, neodymium ammonium nitrate and either potassium bichromate or eosine form an excellent combination. The former absorbs the yellow lines, and the latter the blue lines. Neptune green *S* and chrysoidine have been recommended for the purpose, but the author has found the former method more satisfactory. A cell of water will cut off the infrared rays satisfactorily for most cases when this is necessary.

For isolating the blue line, 0.4359, cobalt blue glass and aesculine or sulphate of quinine form a satisfactory combination. The lines 0.4047 and 0.4078 μ can be practically isolated by a combination of methyl violet and sulphate of quinine in separate solutions. The line 0.3984 is transmitted to a slight extent.

The ultra-violet line, 0.3650, can be practically isolated by methyl violet 4*R* and nitrosodimenthyl aniline, methyl violet and acid green, or resorcine blue and aniline green.

By the use of other line spectra and ruby glass or red dyes, monochromatic red light can be readily obtained.

R. W. Wood has used a combination of strong cobalt-blue glass and a strong yellow, such as a saturated solution of bichromate of potash, for isolating the infrared rays beyond 0.69 μ. In photographs of a landscape through this filter the sky appears comparatively black and the foliage white.

Only the near infrared rays and no visible rays are transmitted by a solution of iodine in carbon bisulphide in a cell whose sides are composed of dense red glass. Wood has used lenses coated with

a thin film of chemically deposited silver for ultra-violet photography. Such a film is opaque to all rays excepting a narrow region in the vicinity of 0.32μ. The formulæ for silvering are readily found in any recipe book.

Many of the organic dyes and colored glasses are useful as filters, depending upon the requirements. It is possible by a careful choice of filters and light sources to isolate any region of the spectrum desired. Photographic plates, owing to their diversity in spectral sensitivities, are valuable assets in some problems. Filters are often much more satisfactory in providing monochromatic illumination than the spectroscope, owing to the much greater intensities of radiation obtainable.

An experiment which is very useful and educative is the comparison of two yellows of different spectral compositions. A solution of potassium bichromate in water transmits yellow rays. If to a portion of this solution an aqueous solution of neodymium ammonium nitrate be added, the spectral yellow rays are no longer transmitted. The two solutions (*c* and *d*, Fig. 17) appear yellow in daylight. If not exactly of the same color, they can be readily brought to the same appearance by the use of more or less of the potassium bichromate in one of the solutions or by the addition of one of the yellow or orange dyes. It has been said that color depends upon the wave-length of light. However, color can not always be taken as an indication of wave-length,

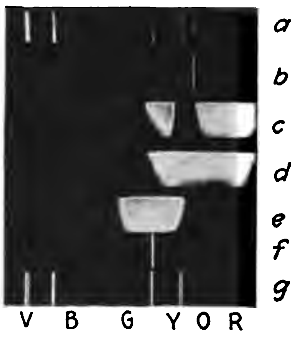

Fig. 17.—Screens for producing lights of the same hue but differing in spectral character.

because, as in this case, the two solutions appear of the same color — yellow; yet when examined by means of the spectroscope one (*d*) is found to transmit green, yellow, and red rays, while the other (*c*) transmits no yellow rays — only the green and the red rays. The latter is said to produce a subjective yellow. The transmissions of the two solutions are shown in Fig. 17 compared with the spectrum of the mercury arc (*g*). It is seen that the absorption band of solution *c* falls in the same region as the yellow mercury lines, 0.5790μ and 0.5764μ, so that these yellow lines will not be transmitted by it. Therefore, since the yellow solutions are not transparent to the rays of shorter wave-length, the solution containing the neodymium ammonium nitrate (*c*) will, when illuminated by the mercury arc, only transmit the green line, 0.5461, as shown in *f*. On viewing a mercury arc through each of the two solutions this is readily verified; one solution then appears a brilliant green, while the other remains yellow in color. The color of the green mercury line can readily be matched by a combination of colored glasses and dyes. The transmission of this combination filter is shown in *e*. The two yellow solutions *c* and *d* were made to match the yellow sodium lines, 0.5890 and 0.5896, which are shown (unresolved) in *b*. These lights, of the same color but of different spectral character, obtained with these solutions and properly chosen illuminants, were used in various interesting experiments to be discussed later (#37).

An exhaustive spectrophotographic treatment of the transmission spectra of filters is outside the scope of this treatise, but a number of spectrograms of useful filters and ordinary glasses are given in Figs. 18 and 19. Uhler and Wood[8] have prepared a

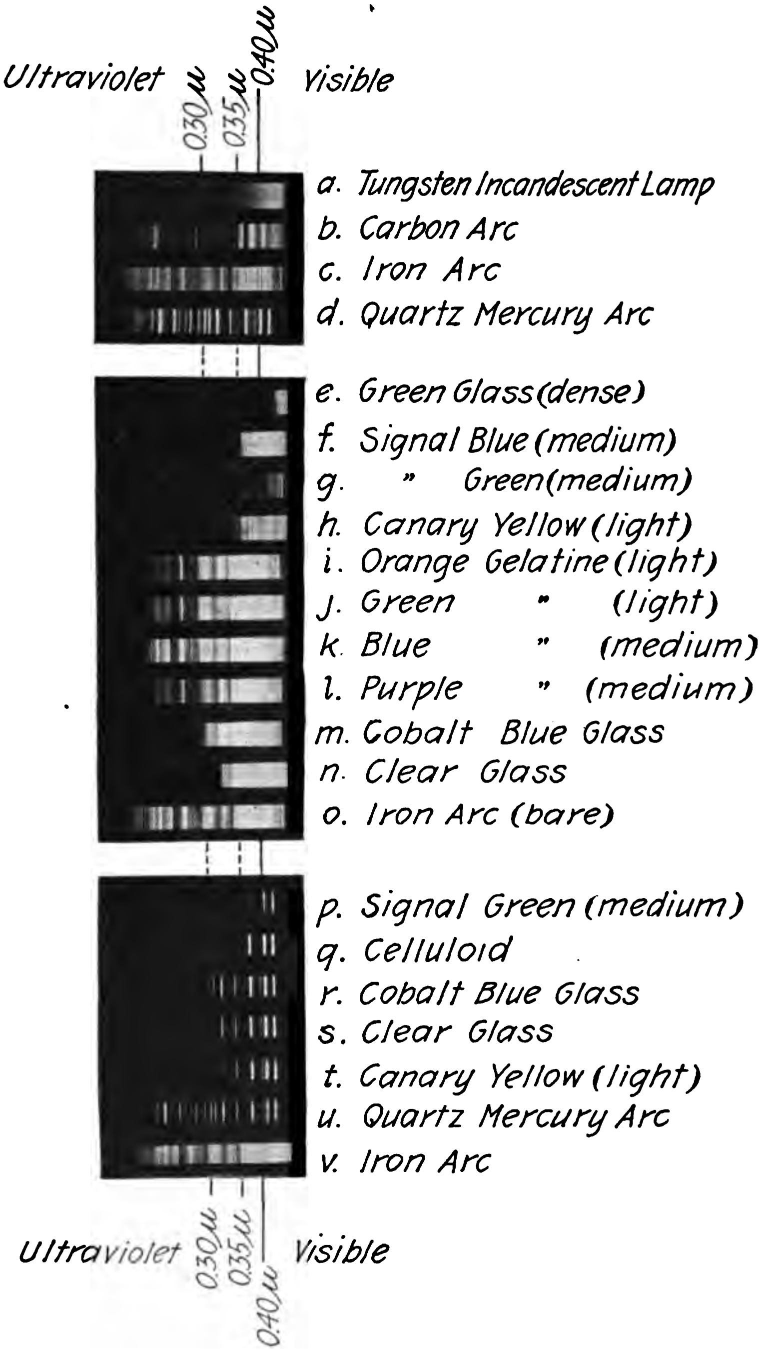

Fig. 18.—Ultra-violet spectra.

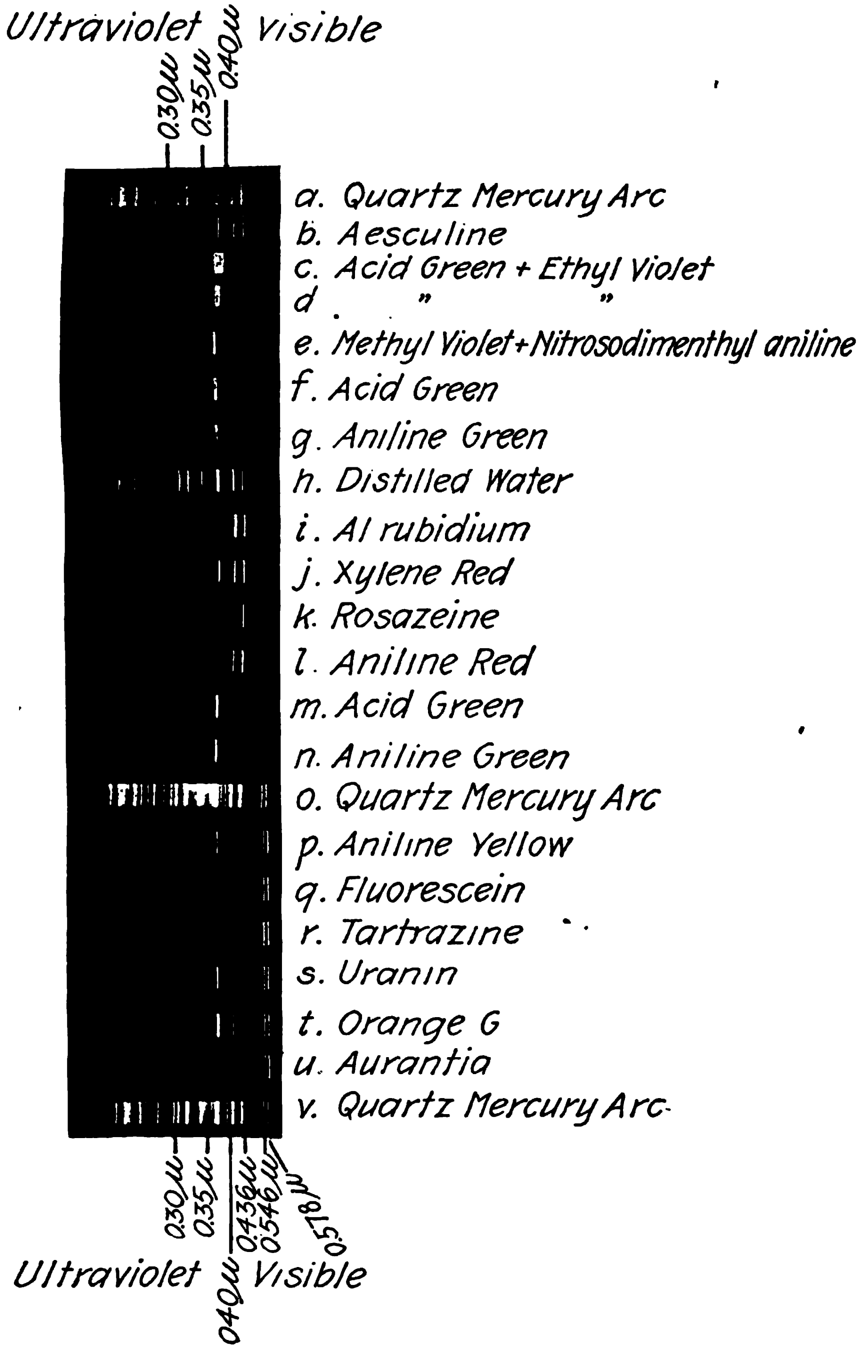

Fig. 19.—Ultra-violet spectra.

valuable atlas of absorption spectra, and C. E. K. Mees [9] has prepared a similar treatise dealing with organic dyes. The spectrograms in Fig. 18 and those from *i* to *v* in Fig. 19 were photographed on Cramer spectrum plates, which are sensitive, but in varying degrees, to all visible and ultra-violet rays transmitted by quartz. Spectrograms *a* to *h* (Fig. 19) inclusive were made on an ordinary plate not appreciably sensitive to rays of longer wave-length than 0.48μ.

In Fig. 18, *b*, *c*, *d*, show the spectra of sources rich in ultra-violet rays. The next group, *e* to *o* inclusive, shows the transmission of common glasses for the radiation from an iron arc. The last group shows the transmission of some of the same glasses for the radiation from the quartz mercury arc.

In Fig. 19 are shown the transmissions of various special screens. These screens are all cemented between two polished glass plates, each one-eighth inch in thickness. The glass is transparent to rays as short as 0.350μ, but begins to absorb at this point, becoming practically opaque to ultra-violet rays shorter than 0.300μ. Some of the first spectrograms illustrate the ability of specially prepared filters to isolate a narrow region of the ultra-violet spectrum at 0.365μ. For instance, acid-green transmits this ultra-violet line, but also transmits much visible light not shown in the spectrogram on account of the scarcity of the transmitted visible rays in the spectrum of the mercury arc. However, by combining with this screen a visual complimentary dye, such as ethyl violet (a purple), which likewise transmits line 0.365μ but practically none of the visible rays transmitted by the acid-green, a visually opaque screen is produced which transmits rays near 0.365μ quite readily. In much the same manner combination screens are

devised for isolating any region of the spectrum. There is no limit to the number of screens that may be combined. The author has at times found it necessary to use as many as five dyes in combination to obtain the desired results. In Fig. 19, *p* to *u* inclusive show the rays in the quartz mercury arc radiation transmitted by six different yellow screens between glass plates. These screens appear of about the same color and transparency in daylight. All are seen to transmit the yellow and green mercury lines, but three of them also transmit ultra-violet rays. Data regarding other media and the relative exposures and transparencies to tungsten light have been presented elsewhere.[10] The original negatives are of course more satisfactory than the prints, because some of the fine detail is unavoidably lost in reproduction. These few specimen spectrograms have been inserted, not only on account of the interest in these special cases, but also as a means of giving some idea of the various details to be considered in the examination and production of special screens to those who may not be familiar with the procedure.

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CHAPTER III

COLOR-MIXTURE

17. That there is a tremendous variety of colors present in Nature can hardly escape the most indifferent observer. A glance at a modern painting reveals the same abundance of tints and shades of color created by the hand of the artist from a few well-chosen fundamental colors. The artist mixes colors in a qualitative manner. He sometimes begins painting with some knowledge of the science of color-mixture, but after all his knowledge of mixing colors is largely qualitative and based upon association with his stock of pigments rather than upon a knowledge of quantitative mixture of spectral colors. His success lies largely in a thorough acquaintance with the tools at his disposal, which are his pigments, yet an acquaintance with the science of color is of incalculable value to him, for the experimental results of the scientific study of color-mixture have largely formed the foundation of pure and applied art as well as of modern color theories.

18. *Subtractive Method.* — There are two distinct methods of mixing colors; by addition and by subtraction of light rays. In a sense, color, as we ordinarily encounter it, is produced primarily by subtraction (#12). That is, a fabric appears colored as a rule because the chemical used in staining it has the property of absorbing certain visible rays and of reflecting (or transmitting) the remaining rays. This subtraction of colored rays from white light

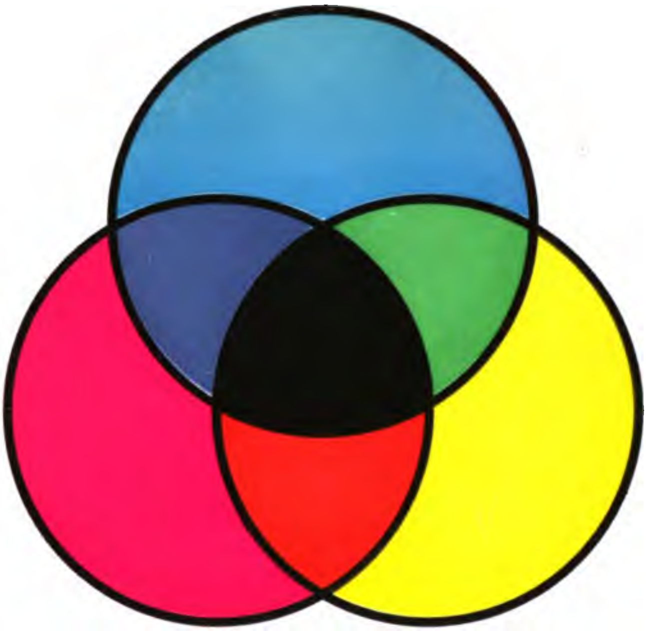

Plate II. Fig. 20. The Subtractive Method of Mixing Colors

Plate II. Fig. 21. The Additive Method of Mixing Colors

results in the residual colored light. The integral color of the light absorbed is said to be complementary to the color of the light remaining if the total light in the beginning were white light, say noon sunlight. Of course in the foregoing case the absorbed color has disappeared, so there is no opportunity to view the complementaries. Any pair of complementary colors can be readily viewed by a comparatively simple apparatus. By means of a prism the spectrum of sunlight is produced at some point in space. A portion of this spectrum can be deflected from the original path by means of a prism of slight angle. The rays in each beam can be combined upon adjacent spots of a white surface by means of lenses, with the result that instead of a spot of white light two adjacent spots of colored light are seen. These two colored lights are obviously complementary, for if they are made to overlap they will be found to produce, by addition, a white light. By separating various portions of the spectrum all the pairs of complementary colors are readily presented to view. As will be shown later, white light can be matched by mixing certain pairs of (and also by mixing three or more) spectral colors. This can readily be demonstrated by means of variable slits cut in a cardboard screen and held in front of the spectrum. If the slits have been placed in their proper position in the spectrum and properly adjusted in width, white light will result when the rays from these slits are combined on a white screen by means of a lens.

The subtractive primary colors have been termed red, yellow, and blue. In reality they would be more exactly described as purple, yellow, and blue-green. They are the complementaries of the additive pri-

maries, as will be seen later. Some may prefer to use the term 'pink' or 'magenta' instead of 'purple', but the hue is a purple consisting of red and blue. The tri-color processes of printing and color photography are based upon the subtractive principle of mixing colors.

The principle of the subtractive method is well demonstrated by Fig. 20 (Plate II). If the three subtractive primaries, purple, yellow, and blue-green, are carefully made by the use of transparent media, water colors or printing inks, and are superposed, the results shown in Fig. 20 are obtained. First let us take a simple case of a yellow pigment on a white surface. The light passes through the colored film and is reflected back through it by the white surface. As the light passes through the yellow pigment it is robbed of the violet and blue rays, therefore the light which reaches the eye is white minus violet and blue rays, and produces a sensation of yellow. In the processes of painting and color printing the three disks may be assumed to be microscopic in size, each being a minute flake of pigment. If two flakes be superposed, a yellow above a blue-green, a green color is obtained. The yellow flake does not transmit blue rays, therefore the green rays are the only remaining rays that will be transmitted by the blue-green pigment. These will be reflected by the white surface, and will pass again through the blue-green and yellow pigments, undergoing further changes tending to purify them, so that only green rays reach the eye. If the blue-green flake is above the yellow flake, the explanation must be reversed, but with the same result. The blue-green flake transmits blue and green rays; however, the yellow flake does not transmit blue rays. Therefore, only the

green rays will eventually be reflected to the eye. In the same manner the blue of the purple is subtracted by the yellow flake, and as purple consists of red and blue rays only, the red rays remain to be reflected to the eye. Therefore, yellow and purple flakes superposed produce red. Likewise the blue-green flake does not transmit red light, so that superposition of blue-green and purple flakes results in blue light being reflected to the eye. It is further seen that the superposition of the three subtractive primaries results in a total extinction of light and black is the result. For instance, where the yellow and purple disks overlap, red results. The blue-green disk does not transmit red rays, so where it overlaps the red disk a total extinction results.

Much interesting information may be obtained by carefully studying Fig. 20. Strips of colored gelatine laid over each other in checkerboard fashion present many striking examples of the subtractive method of mixing colors. In ordinary artificial light, screens made of ethyl violet (purple), uranin or aniline yellow, and filter blue-green, are excellent dyes for making the subtractive primaries for demonstrating the foregoing by superposition. Ethyl violet and naphthol green are practically complementary, so that when superposed no light rays are transmitted.

19. *Additive Method.* — As already indicated, there are two distinct methods of mixing color, — the additive and subtractive, — but close investigation often reveals both processes entering into some part of the production of color. The additive method always tends toward the production of white, whereas the subtractive method tends toward the production of black. The additive primaries are red, green, and blue. Some prefer to use the term 'violet' instead

of 'blue.' Blue, however, appears satisfactory and is a safer term than violet, because there are a great many who apply the term violet to purples.

Long ago it was demonstrated that, by proper mixtures of the three well-chosen primary colors, any color can be matched. This is largely due to the fact that the eye is a synthetic rather than an analytic instrument. In Fig. 21 (Plate II) are illustrated the principles of color-mixture by the additive method. It is seen that red added to green produces yellow; and further, when blue is added to this combination white is produced. In other words, yellow and blue mixed by addition produce white. It is well known, however, that yellow and blue (in reality blue-green) pigments when mixed by the subtractive method, as is done in painting and color printing, produce green. This is a much confused point, but is very simply explained when the character of the procedure of mixture is analyzed. Red and blue when added produce purple; and blue and green produce blue-green. It is to be noted that combinations of two of the additive primaries produce the subtractive primaries and vice versa. The additive method can be readily demonstrated by the use of colored lights projected upon a white surface. Properly selected color-screens are necessary, but can be readily made from aniline dyes by carefully mixing them. It is difficult to describe the procedure quantitatively, but there is no difficulty in producing the proper colors.

Owing to the very unsatisfactory state of color terminology, it is impossible to present an accurate and definite list of complementary hues. However, a few complementaries are given in Table IV.

TABLE IV

Complementary Hues

Red	Blue-green (Cyan blue)
Orange-red	Green-blue (bluish cyan)
Orange	Blue
Yellow	Blue-violet
Yellow-green	Violet-purple
Green	Purple (magenta)

Wave-length of Complementary Spectral Hues

0.6562 μ	0.4921 μ	.5671 μ	.4645 μ
.6077	.4897	.5644	.4618
.5853	.4854	.5636	.4330
.5739	.4821		

An excellent scheme for showing the complementaries is to arrange the spectrum around the circumference of a circle filling a gap between the ends of the spectrum, violet and red, with a series of purples from bluish purple to reddish purple. This has been called a color wheel, and is diagrammatically shown in Fig. 22. Here yellow and violet are shown as complementary. This may appear inconsistent with the foregoing discussion, but it will be noted that the terms 'blue' and 'violet' (as well as other color names) are indefinite. The term 'blue' will always mean a spectral blue, but when used as a primary color its hue is definite, whether the term stands for blue, violet, or blue-violet. If the complementaries have been correctly applied to the color wheel, a neutral gray should be obtained when it is rapidly rotated.

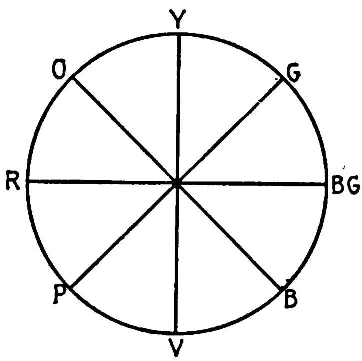

Fig. 22.—The color-wheel for showing complementary hues.

20. *Juxtapositional Method.* — If a color be broken up into its component colors and the latter be applied in small dots with the point of a brush, the sensation of the original color will be obtained if it be viewed from a distance at which the eye is unable to resolve the individual dots and providing the relative areas covered by the various colored dots are correctly balanced. Colors, excepting those encountered in the spectrum, are usually far from monochromatic (#12), (Figs. 122, 123). For instance, a colored fabric which may appear a pure red will be found to reflect rays throughout considerable range of wave-lengths. If these component colors be represented as pure as possible in minute dots of proper relative amounts, the foregoing result is readily obtained. For instance, if one end of a pack of cards be painted red and the other end green, on reversing every other card and viewing an end of the pack at a distance of several feet, it will appear yellow in color. The brightness apart from hue will be an average brightness. Many interesting experiments can be performed by ruling alternate fine lines of different colors on paper or on glass. For instance, purple and green lines alternated on paper will, if well chosen, produce an appearance of gray at some distance. Such a method of breaking a composite color into more nearly monochromatic components and applying the latter in the form of minute dots is the foundation of the principle of impressionistic painting. The processes of color photography devised by Joly, Lumière and others are also based on this principle.

21. *Simple Apparatus for Mixing Colors.* — There are very elaborate color-mixing instruments on the market for the purpose of demonstrating the

theory and practise of color-mixture. Apparatus that deals with spectral colors is as a rule the most satisfactory for accurate study and demonstration. However, inasmuch as the colors ordinarily available in practise are far from monochromatic, that is, far from spectral purity, there is much virtue in the simpler forms of apparatus that can be made at small expense. In fact, for the foregoing reason the results obtained with some of the simpler instruments for demonstration are more readily interpreted and applicable in practise than those obtained with apparatus dealing with pure spectral colors.

Maxwell's disks offer a ready means for mixing colors. A shaft is arranged so as to be revolved at high speed. Colors painted on a disk can thus be mixed by rotating it at a high speed owing to persistence of vision. Light sensations do not reach their full value immediately upon application of the stimulus, nor do they decay to zero immediately upon the cessation of the stimulus. An infinite number of mixtures of pigments, including black and white, can be made with such a simple disk. Colored papers cut in circles and slit along one of the radii can thus be overlapped to any degree, and by the use of circles of various sizes a number of mixtures can be produced upon the same disk. This method is not truly an additive one, excepting in the addition of hues. The brightness is the mean of the separate brightnesses, each weighted by its angular extent. In Fig. 23 are typical color disks for mixing colors to produce grays. In I and III are represented pairs of complementary colors respectively, yellow and blue, and green and purple. The inner circle consists of black and white, which can be varied in angular amounts to produce a neutral gray to

match the gray produced by the addition of the two hues. In II are represented the three primary colors which when mixed by rotation produce a neutral gray which is readily matched by means of the inner black and white disks. These matches made under one illuminant will not ordinarily remain matches under another illuminant. Much of the early work in the science of color was done by means of rotating disks and even today they are extremely valuable in some investigations. The disks represented in Fig. 23 can be readily made from Zimmerman's

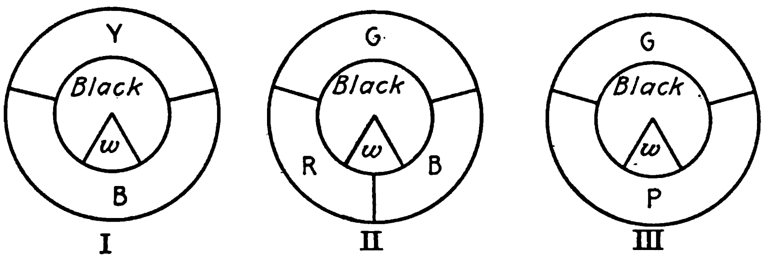

Fig. 23.—Maxwell disks.

colored papers. These papers are indicated in the catalogue by the letters of the alphabet and are given herewith as used in the disks already described. Yellow is designated as *g*, blue as *o*, green as *i*, red as *b*, and purple as *a*. For the black and white sectors any neutral tint papers with dull finish are satisfactory for producing the grays.

The additive and subtractive methods as illustrated in Figs. 20 and 21 (Plate II) can readily be demonstrated in permanent charts. The imported colored papers have been found satisfactory, owing to their comparative purity and unglazed surfaces. For demonstrating the subtractive method by the three overlapping disks the six colors and black are surrounded with a white background. The Zimmer-

man colors, designated by *a*, *g*, *l*, *b*, *i*, and *o*, may be used respectively for purple, yellow, blue-green, red, green, and blue. These six colors, with black and white, are sufficient for the construction of charts for the additive and subtractive methods. For demonstrating the additive method the three disks should be surrounded with black background, but in the case of the subtractive method the background should be white. For demonstrating these two methods of color-mixture with artificial light by means of transparent media, purple and green are readily produced by using gelatines dyed with ethyl violet and naphthol green respectively. When these two colored gelatines are superposed in proper densities of coloring, no light is transmitted. When light is passed through these media in juxtaposition in proper relative amounts and combined on a neutral tint diffusing surface a white light is produced. These two colors afford an excellent example of complementary colors when used with artificial light. In daylight the ethyl violet screen appears deep blue in color, instead of appearing purple as it does in the light from a tungsten incandescent lamp. Other transparent media for further demonstrating these methods are readily selected from the many organic dyes available. Uranin, fluorescein, carmine, patent blue, and filter blue-green are satisfactory.

In Fig. 24 the construction of an erratic color-mixing disk is illustrated. To a disk of stiff cardboard a sectored disk of cardboard is rigidly fastened by means of a circular rivet. The latter disk has two 60° openings, as shown in *a*. Another disk, arranged concentric with the other disks and between them, is permitted to slip at will about the rivet as an axis. If the latter disk is prepared as shown in

b many striking colors are obtained on rotating the combination.

Fig. 25 illustrates a simple arrangement for color-mixing. The wheel is similar to that employed in the Simmance-Abady flicker photometer. The periphery

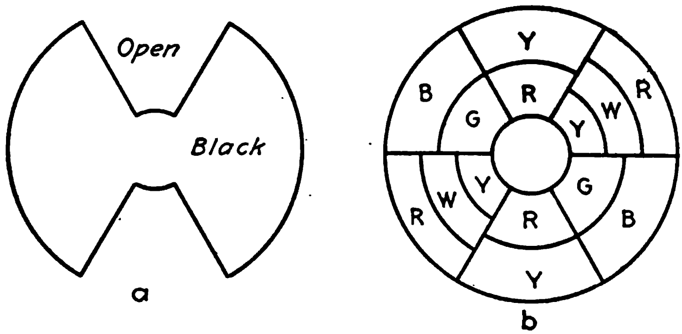

Fig. 24.—An erratic color-mixing disk.

of this wheel consists of truncated cones pointing in opposite directions. The axes of the cones are eccentrically placed at equal distances on either side of the axis of the wheel and parallel to it. In the angular position shown in the illustration,

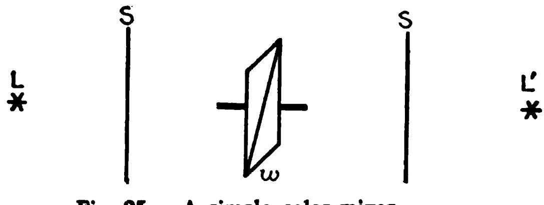

Fig. 25.—A simple color-mixer.

the eye, looking at the wheel in a direction at right angles to the axis, sees one conical surface illuminated by one light, *L*, and the other by the other light, *L'*. Colored screens, *SS*, are interposed between the wheel and the light sources. By having the lamps movable on a track any combination of brightnesses of two colors from transmitting media can be mixed

by rotating the wheel rapidly. Pigments may also be applied directly to the wheel.

In Fig. 26 is illustrated another simple instrument for mixing the colors from either opaque or transparent media. A wooden box is constructed as shown and painted black inside. *G* is a transparent plate glass and *OO* are ground opal glasses free from color. In mixing the colors of two transparent media, *CC*, the lamp, *L*, is moved to and fro on its track. Thus any proportions of the two colors can be mixed. If the colors of two opaque substances are to be mixed, *CC* and *OO* are removed, the colored objects are placed at *PP*, and the lamp is moved to and fro as before. The range of mixtures in the last case is not infinite as in the case of transparent media; however, modifications can readily be made so that the range is extended.

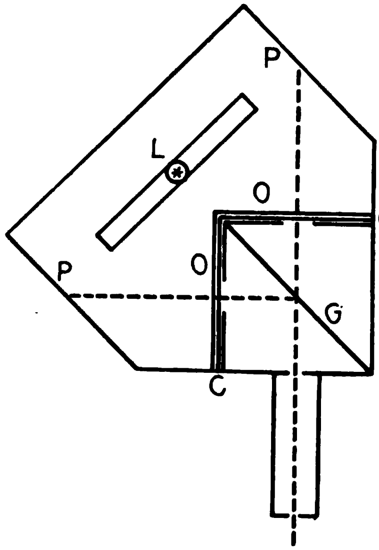

Fig. 26.—A simple color-mixer for transparent or opaque media.

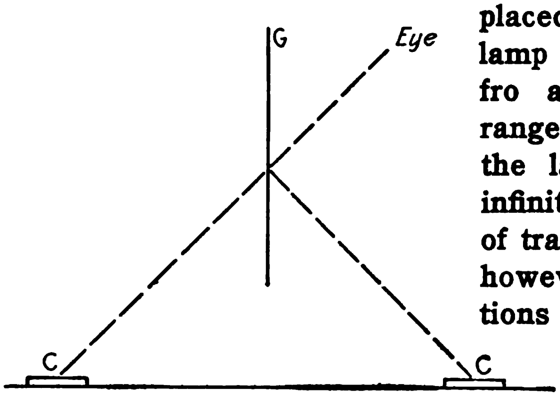

Fig. 27.—Lambert's color-mixer.

A simple experiment devised by Lambert, though not having the flexibility of the foregoing instruments,

is of interest owing to its extreme simplicity. It is illustrated in Fig. 27. *G* is a plate glass and *CC* are colored objects. The colors are mixed one by reflection, the other by transmission. By turning the glass and shifting the eye the proportions can be altered considerably.

An apparatus of considerable use is a booth containing red, green, and blue incandescent lamps controlled by rheostats. If the colors are carefully made many interesting experiments can be performed, including the effect of quality or spectral character of light upon colored objects (#67).

Many instructive experiments can be produced by the use of shadows cast by colored lights. One of especial interest is shown in Fig. 28, because it presents the additive primaries, their complementaries (the subtractive primaries) and white light produced by the sum of the three primary colors, — red, green, and blue. In the middle of a circle of white diffusing blotting paper stiffened by a board are erected three planes of white diffusing material about eight inches in height. The latter meet at the center of the circle at angles of 120 degrees with each other. At points several feet away, along the three arrows, red, green, and blue lights are placed somewhat above the plane of the circle. These should be small sources and quite powerful, concentrated tungsten filament lamps being quite satisfactory. The experiment is best

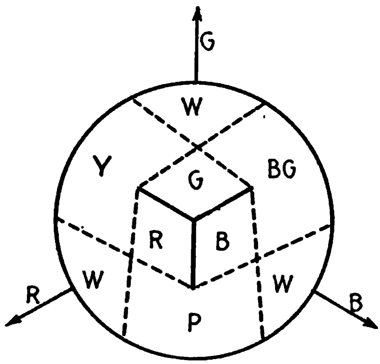

Fig. 28.—A shadow demonstration of the additive and subtractive methods of color-mixture.

seen if the plane of the circle is vertical. It will be seen that the nearly rhombic areas on the circle indicated by *R*, *G*, and *B* each receive light from only one source. These areas will then appear respectively red, green, and blue. The areas on the opposite sides of the circle, *BG*, *P*, and *Y*, each receive light from only two sources. They appear in colors complementary to the above primaries. They also represent the subtractive primaries and the colors which remain after red, green and blue are subtracted respectively from three white lights. The remaining areas of the circle marked *W* represent the regions which receive light from each of the three sources, with the result that if the colors and intensities of the light sources are correct, and if the sources are sufficiently distant in comparison with the size of the circle, these areas appear a uniform white. This experiment is simple and is very satisfactory for demonstration before large audiences. The lights should be controlled by separate switches and rheostats.

A rotating disk can be readily colored, so that it will appear, when viewed through a radial slit placed close to it, a fair approximation to the spectrum. The mixing of the colors by rotation obviates the necessity of the great care in blending colors in painting a spectrum that is to be viewed when stationary. The colors will not be of spectral purity, owing to the limitations of the pigments, but the disk will be instructive and affords a ready means of producing a spectrum for reproduction by color photography. An approximation to the prismatic spectrum can be readily produced as shown in Fig. 29. The approximation can be made as close as desired by touching up various points with pigments where necessary or by varying the geometric figures. If a circle be cir-

cumscribed about the inner square and a square in turn be circumscribed about this circle, and so on until four circles and four squares are produced, the skeleton of the figure is ready for coloring. If the inner square be painted black and the succeeding hollow squares be painted red, yellow, green, and violet respectively and the remainder of the outer circle be painted black, a fair approximation to a prismatic spectrum is obtained. The same results can be produced with more difficulty with only three colors —red, green, and blue. If the spectrum produced by rotation is not satisfactory at all points, it can be readily made so by the judicious use of pigments, or, as already stated, by altering the geometric figures.

Fig. 29.—Illustrating a disk for approximating a prismatic spectrum.

The more simple methods of mixing colors have been described in this chapter; however, it will be borne in mind that many of the instruments and methods considered in succeeding chapters are directly or indirectly applicable to color-mixture.

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CHAPTER IV

COLOR TERMINOLOGY

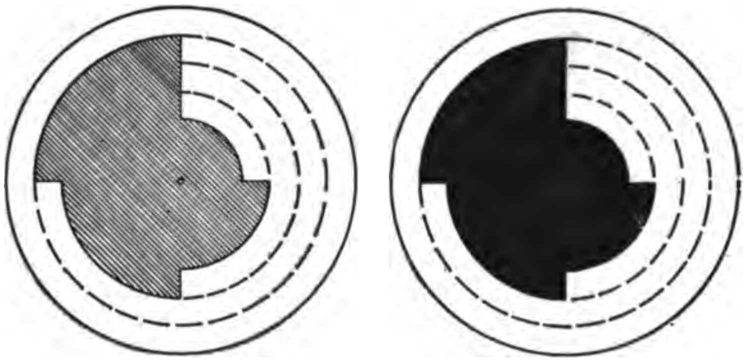
22. *Hue, Saturation, and Brightness.*—One of the greatest needs in the art and science of color is a standardization of the terms used in describing the quality of colors and an accurate system of color notation. The term 'color' in its general sense, is really synonymous to the term 'light.' It is used here by preference because it implies the consideration of the appearance of a surface or material object. The spectrophotometer is the most analytic instrument for examining colors (#26). By means of it the amounts of light of all wave-lengths reflected (or transmitted) by a colored medium may be obtained. These data are plotted in the form of curves shown by the dashed lines in Fig. 12. The full line curves represent the reflection (or transmission) coefficients of the pigments for energy for various wave-lengths. If the region under one of the curves indicated by a dashed line be integrated and this area compared with that obtained with the same illuminant for a white diffusing surface of known total reflecting power, the relative brightness of the colored medium under this illumination is obtainable. The dominant hue which is discussed below may be usually approximately determined by inspection of the curve, although in many cases it is impossible to estimate the dominant hue in this manner. It is thus seen that although the spectrophotometer is a valuable instrument for analyzing colors, there are further require-

ments in color work better met by other instruments (Chapter V).

The quality of any color can be accurately described by determining its hue, saturation or purity, and its brightness. (The latter term is analogous to the term 'value' as used by the artist.) In the broadest sense, white, gray, and black are here considered as colors, and a mere change in brightness alone is considered as a change in color. It appears necessary to assume this broad definition of color, inasmuch as brightness is distinctly one of the products of color analysis. Hue is suggested in the name applied to the color. The dominant hues of most colors are accurately represented by spectral colors; however, there are composite colors, — the purples, which consist of red and violet, for which no spectral colors are found to represent their hues. In these cases it is satisfactory to determine the dominant hue of the complementary colors. The saturation or purity is a measure of the relative amount of white light in the color. In other words, all colors excepting purples can be matched by diluting spectral light of a definite wave-length with white light. The greater the percentage of white light required in the mixtures, the less saturated the colors are said to be. The brightness of a color can be found by comparing it by means of a photometer with a surface of known brightness. It is well to note that in the analysis of a color its absolute brightness is measured by comparing it with a brightness of known value. Inasmuch as its brightness depends upon the intensity of illumination of a given spectral character, its reflection coefficient for a standard white light should be determined in order to compare it with other colors in this respect. This latter measurement in-

volves all the difficulties of color-photometry treated in Chapter IX.

There is much confusion in the application of the terms 'tint,' 'tone,' 'shade,' 'intensity,' etc. Many use these terms wholly unjustifiably. It is true that the final usage is somewhat a matter of choice at the present time, but the terminology adopted here appears to the author to be consistent with other nomenclature adopted by the physicist, photometrist, and



a b

Fig. 30.—Disk 'a,' for varying only the saturation of a color.
— Disk 'b,' for varying only the brightness of a color.

lighting expert, and best justified by usage and the dictates of common sense. On diluting a color with white light, tints are obtained; that is, tints are unsaturated colors. By the admixture of black to a color (in effect the same as reducing the intensity of illumination) the brightness is diminished without altering either the hue or the saturation, and various shades are produced. Only the relative brightnesses of shades are usually of interest, although for obtaining a basis of notation it may be desirable to determine their absolute values. In *a*, Fig. 30, is shown a simple means of varying the saturation of a color without altering either the hue or brightness. On a

circle of colored paper is glued a gray paper of the same brightness for the given illumination and of the form shown by the shaded area. On rotating the disk this gray will be mixed in various angular proportions from 360 deg. to 0 deg. The gray paper, having been selected of the same brightness as the colored paper under the illuminant used in the experiment, does not alter the brightness upon mixing the two components by rotation; being non-selective in its reflection it does not alter the hue. Thus various degrees of saturation of the original color are obtained.

The brightness can be varied, as shown in *b*, Fig. 30, without altering either the hue or saturation by fastening to the original circle of colored paper a black paper cut in the same form as the gray paper shown in *a*. If the paper were perfectly black it is seen that it cannot alter either the hue or saturation. As a matter of fact no available black papers are totally non-reflecting, so that some light is added to the color. This can be reduced to a minimum, however, by the use of a hole in a deep velvet-lined box. In this case the black sectors shown in *b* would be replaced by openings of the same contour in the disk. For convenience of construction the areas occupied by the black and colored papers may be reversed. In this connection it is well to emphasize that ordinary black surfaces are far from totally absorbing. This can readily be demonstrated by a box open at one end lined with black velvet. Over the open end place a black cardboard with an opening in it and it will be seen that the opening will appear very much darker than the black surface surrounding it. The foregoing demonstration may be easily performed by varying the brightness of a colored paper relative to that

of a paper of the same color which surrounds it, by varying the intensity of the illumination of the patch at the same time maintaining the absolute brightness of the surroundings constant.

Instruments have been designed for the analysis of color quality into the three component factors, hue, saturation, and brightness. These are treated in #27.

23. *Tri-color Method.* — It is well known that any color can be matched by combining the three primary colors, red, green, and blue, in proper proportions. Many instruments have been devised for this purpose, the most elementary being the Maxwell disks, and the more elaborate and accurate are those employing spectral colors. The results of such a method are expressed mathematically in the equation $xR+yG+zB=C$, where the values of x, y, and z are the fractional parts of the red, green, and blue lights, respectively, that must be combined to match the color, C. This method has limitations because it does not give the results directly in terms of hue, saturation, and brightness. Some of these instruments, however, can readily be adapted to the measurement of the last two factors. In order to plot the values of x, y, and z, it is necessary to employ tri-linear coördinates, there being three variables to be represented. The results are readily represented in the Maxwell color triangle, illustrated in Fig. 31. The green component increases from zero at the base

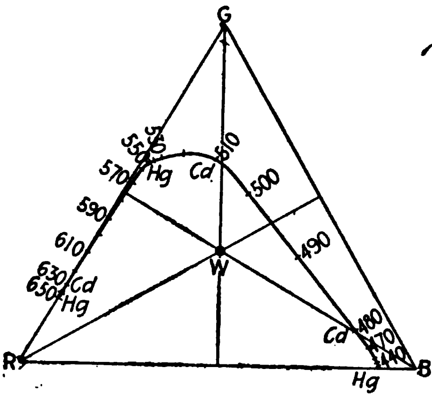


Fig. 31.—The Maxwell color-triangle.

line, RB, to 100 per cent at G. Likewise the red, R, and green, G, components increase from zero at the base of the perpendiculars erected from the sides respectively opposite to their apexes. The data are plotted by erecting three perpendiculars proportional to the respective values of R, G, and B, starting at points in the opposite sides of the triangle respectively, such that the three perpendiculars intersect at the same point. Purples are found along the base line, RB, varying in the proportions of R and B from $R = 0$, $B = 100$, to $R = 100$, $B = 0$. Yellows are found along RG and blue-greens along GB. White, which is usually represented by $\frac{1}{3}R + \frac{1}{3}G + \frac{1}{3}B = W$, is found at the center of the triangle. The curved line represents the positions of the spectral colors in the color triangle; that is, each point on the curve represents the primary sensation values of a particular spectral color. Some important lines of the spectra of cadmium and mercury are also shown. The less saturated colors are found near the center of the triangle and the more saturated ones near the sides. It is thus seen that spectral colors throughout a large range of wave-lengths arouse the three primary sensations, according to the Young-Helmholtz theory. (See #28, 47.) The primaries of course are found at the angles of the triangle. Complementaries are represented as being on opposite sides of the center of the triangle on a straight line passing through it. The dominant hue of a color is found by drawing a straight line from the center of the triangle through the point representing the color and continuing it until it intersects the curve representing the spectrum. The latter point of intersection represents the dominant hue of the color. The tri-color method involves the use of an invariable white light, that is

noon sunlight or its equivalent. A curve representing spectral complementaries is shown in Fig. 32.

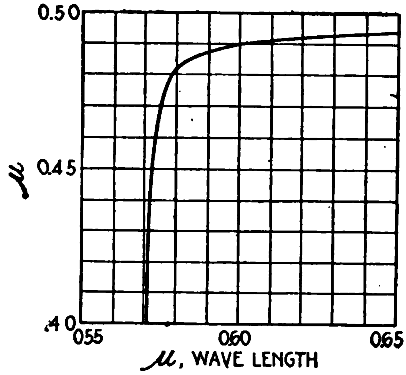


Fig. 32.—Spectral complementaries.

Results obtained by this general method with different instruments are likely to vary considerably. This is due in part to variations in the spectral character of the white light standard, and also to the transmission characteristics of the color-screens used in these instruments not employing spectral primary colors. The primary sensation values of the screens should be determined and the measurements be given in sensation values (#28). The use of the plane triangle is limited to the plotting of the analyses of colors of equal brightness. In order to include the brightness factor the figure takes the form of a solid inverted pyramid, shown in Fig. 33. The various triangular planes parallel to the base represent planes for plotting colors of different brightnesses. The apex represents black. A line joining the point, *W* (white), with the apex passes through a complete range of shades of white, that is, of grays. Along the dotted line from *x* to the apex are a series of colors of constant hue and saturation, but varying in brightness. The color pyramid has been modified in various rays to fit experimental results in-

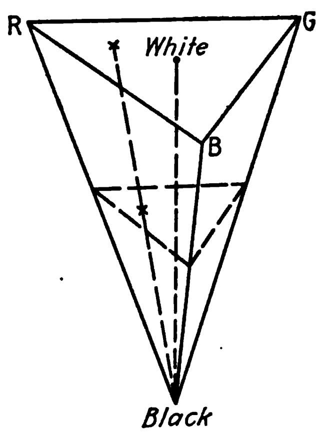


Fig. 33.—A color pyramid.

volving physiological and psychological influences. One of these modifications from Titchener [1] is shown in Fig. 34. At the two poles of this double pyramid are the extremes of white and black; upon the axis connecting the two poles are located the complete range of grays. Around the periphery of the middle plane are located those colors of middle brightness and maximal saturation. Other points in the solid represent other colors of varying hue, saturation, and brightness. From the base toward white, tints are found; in the other direction shades are found. This pyramid, it will be noted, has four sides, the four angles representing red, yellow, green, and blue. Obviously this solid does not directly represent color analyses as obtained by the tri-color method. Its significance will be better understood on referring to the Hering theory of color vision in # 49.

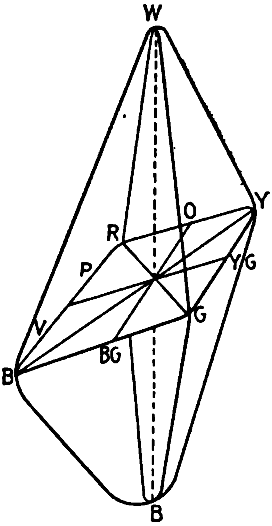


Fig. 34. — The double pyramid. (After Titchener.)

The tri-color method is discussed further in Chapter V. A simple means[2] of demonstrating the Maxwell color triangle in actual colors is illustrated in Fig. 35. A box 6 inches in depth, and whose section forms an equilateral triangle about 18 inches on a side, is made of wood, with its back containing vent holes. A ground flashed-opal glass in the form

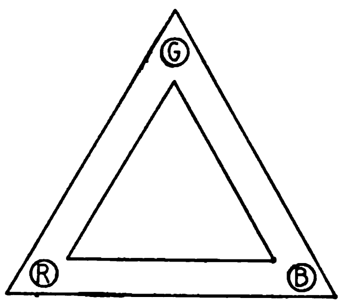


Fig. 35. — A demonstration color triangle.

of an equilateral triangle somewhat smaller than the section of the box forms the front side. In the three corners of the box are placed respectively, red, green, and blue spherical-bulb, concentrated-filament tungsten lamps. After proper adjustments of the position and color of the lamps, the diffusing glass, which has its roughed side inward, assumes the colors of a color triangle. A close approximation can be approached, depending upon the care exercised in adjusting the position of the lamps and the distribution, color, and intensity of the light. Interesting demonstrations of retinal fatigue and after-images are readily made with this simple apparatus. For coloring the lamps ordinary colored lacquers are satisfactory if properly mixed to obtain the exact hues. The aniline dyes can be used with satisfaction. These colors are not permanent, but are sufficiently durable for such an apparatus. If the coloring is placed on separate plates of glass, it will remain unfaded for a long time with proper ventilation.

24. *Color Notation.* — The need for a universal color notation is admirably illustrated by Munsell[3] in quoting from a letter by Robert Louis Stevenson, writing from Samoa to a friend in London, as follows:

"Perhaps in the same way it might amuse you to send us any pattern of wall paper that might strike you as cheap, pretty and suitable for a room in a hot and extremely bright climate. It should be borne in mind that our climate can be extremely dark too. Our sitting room is to be in varnished wood. The room I have particularly in mind is a sort of bed and sitting room, pretty large, lit on three sides, and the colour in favour of its proprietor at present is a topazy yellow. But then with what colour to relieve it? For a little work-room of my own at the back I should rather like to see some patterns of unglossy — well I'll be hanged if I can describe this red — it's not Turkish and it's not Roman and it's not Indian, but it seems

to partake of the two last and yet it can't be either of them because it ought to be able to go with vermillion. Ah, what a tangled web we weave — anyway, with what brains you have left, choose me and send me some — many — patterns of this exact shade."

Here is a man accustomed to present his thoughts in writing in a clear manner, yet he acknowledges failure in his effort to describe colors and closes his letter with the request, perhaps a bit sarcastic, that he be sent "patterns of this exact shade." Other sciences have exact and practically universally accepted terminology. Music has its well-developed notation, which is definite and descriptive, and quite universal in adoption, but there is no universal scheme of color notation. Colors are named in very inexact, unwieldy, and often totally non-descriptive terms. We have rose, Indian red, Alice blue, pea green, olive green, cerise, taupe, baby blue, Copenhagen blue, king's blue, royal purple, invisible green, etc. Thus flowers, vegetables, cities, the savage and the royal family, are used to describe colors. Is there a more ridiculous instance of neglect? Those who work in color often find themselves helpless in describing colors to others. Surely a color notation based upon color science should be acceptable, even though somewhat empirical. Musical notation is somewhat arbitrary, yet it has met with almost universal adoption. An acceptable color notation must involve the factors which influence the quality of a color, namely hue, saturation, and brightness.

An attempt was made by Runge as early as 1810 to build up a color notation by the use of a sphere with red, yellow, and blue, placed around the equator and separated from each other by 120 degrees, with white and black at opposite poles. Perhaps the greatest virtue in this attempt is the fact that it was

one of the early constructive efforts. Chevreul, whose work on the effect of simultaneous contrast of colors in the practical textile industry is well known, constructed a hollow cylinder built up of ten sections perpendicular to the axis. Around the upper section red, yellow, and blue were equally spaced. The lowest cylindrical section was black, and the eight intervening sections were graded from top to bottom by adding increasing amounts of black. Munsell criticises these attempts, on account of the yellow being very light and the blue being very dark, which makes impossible any coherency in the brightness scales of the three colors. Inasmuch as the brightness scale of the yellow in the Chevreul color cylinder increases much more rapidly from the bottom toward the top than the brightness scales for blue and red, Munsell suggests that the yellow side of the cylinder be increased in length. This would result in the tilting of the sections more and more as the scale of brightness progressed from the bottom toward the top. Perhaps a general criticism for most of these schemes of color notation is that geometrical figures are chosen and the colors are made to fit. The latter method is perhaps partially justifiable from the standpoint of physical measurements. There is another viewpoint in considering a color notation, and that is from the standpoint of harmony of color. In this treatise we are not so much concerned with the latter viewpoint, but it is of interest to consider a system of color notation devised by Munsell from the standpoint of the use of color in painting. In describing a color by this system the initial of the name of the color indicates the hue, and numerals represent the saturation and brightness. For example R_7^5 represents a color whose hue is red and whose

saturation and brightness are respectively 7 and 5. The brightness scale is divided into ten parts, and the degrees of saturation shown vary with the brightness. For simplicity ten hues are balanced around the equator of the sphere somewhat after the manner shown in Fig. 22. The lower pole of the sphere is black and corresponds to zero on the brightness scale. The upper pole is white and corresponds to brightness 10 on the same scale. On slicing off a portion of the sphere through a plane corresponding to a certain brightness, various degrees of saturation are encountered. The saturation decreases toward the center, the axis of the sphere consisting of a scale of gray *S*. However, the sphere does not completely satisfy Munsell. He therefore constructs a 'color tree' so that varying numbers of steps in saturation can be represented, depending upon the hue and position in the brightness scale. The scheme is built up on the principle of the harmonious use of colors and in this respect departs somewhat from the scope of this book, which treats more with physical mixtures, regardless of the use of colors in harmony. The system is an interesting one and is the result of a noteworthy attempt to be freed from a state of color anarchy.

Munsell's color tree is illustrated in simple form in Fig. 36. The base of the tree is black, the top white. In the small model illustrated three brightness levels are shown, namely 3, 5, and 7 in the arbitrary brightness (value) scale. The degrees of saturation shown vary with the 'brightness level.' At 'level 3' in the brightness scale blue is shown to the eighth degree of saturation. By the irregularity in the contour of the planes representing different brightness levels it is seen that the relative number

of degrees of saturation shown for various colors depends upon the brightness level under consideration. At brightness level 3, *PB* (purple-blue) was shown with the highest degree of saturation, namely, 8. At brightness level 5, *R* ranked first in degree of saturation, its highest being 10. At the brightness level 7, yellow was shown with the highest degree

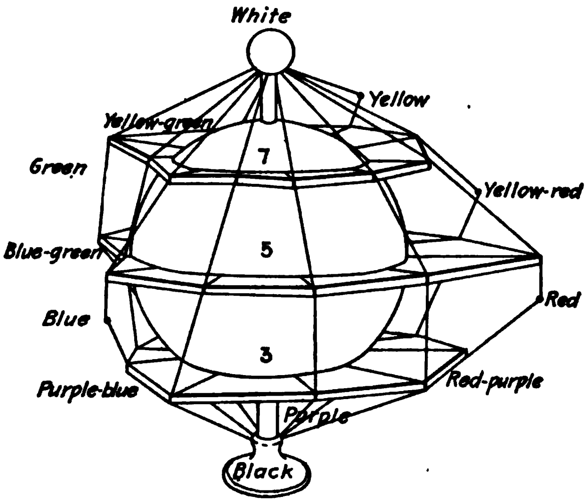


Fig. 36.—The A. H. Munsell color tree.

of saturation, namely 8. For a complete discussion of this system, the reader is referred to the original description by Munsell.[3]

Numerous scales have been devised involving, either separately or combined, the factors hue, saturation, and brightness. All of these assist in bringing order out of chaos, but they constitute only the first steps toward a comprehensive system of color notation. The hues are usually expressed by names of spectral colors and purple, but the brightness is seldom more definite than is found in such expressions as *W*, *HL*, *L*, *LL*, *M*, *HD*, *D*, *LD*, and

B, which represent white, high light, light, low light, medium, high dark, dark, low dark, and black respectively. Examples of such charts (devoid of color) are shown in Fig. 37. These were taken from Book VI of Prang's text-book of art education. Such

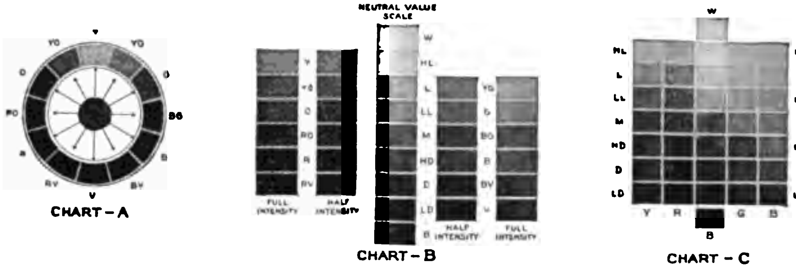


Fig. 37.—Prang's color and brightness scales.

charts should pave the way toward a final scientific color notation.

Another system of color notation is shown in Fig. 38. This is used by Ruxton in the mixture of

Fig. 38.—Ruxton's color mixture chart for printing inks.

printing inks. The chart is printed in colors, there being 144 colors, varying in hue, saturation, and brightness. The terminology is somewhat different than used in this text. The 144 colors are obtained from six fundamental colors, namely red, orange, yellow, green, blue, and purple. These six colors are described as spectral colors, so it is likely that purple

is the name applied to a color meant to be violet. The starting point in obtaining the total array of colors is in the bottom row of Section 3. The larger rectangles represent the six fundamental colors, which are the purest or most saturated on the chart. The fundamental red is marked 820. The small square areas represent the intermediate hues and are obtained by mixing the fundamentals on either side. Red-orange for instance is obtained by mixing red and orange (820 and 840). The three horizontal rows above this row of twelve colors are made by adding white to the colors of the bottom row. Thus in the top row are found the least saturated colors in Section 3. Two degrees of saturation lie between the top and bottom rows. Thus in Section 3 there are 48 colors, six fundamental colors increased to twelve by mixing adjacent fundamentals (red and violet are mixed, producing 810) and these twelve colors decreased in saturation in three steps by the addition of white. Sections 1 and 2 are produced by adding black to the corresponding colors in Section 3, thus reducing their brightness. In Section 1 are the colors of lowest brightness. These are named 'hues' but in a different sense than that in which the term 'hue' is employed here. They could be termed 'Values' with better consistency. The 'bi-hues' (bi-values) in Section 2 are obtained by mixing one part by weight of the colors in Section 3 to one part of the corresponding color in Section 1. Thus it is seen that in a more correct sense there are twelve hues represented on the chart (bottom row in Section 3). With the hue and brightness constant saturation is found to be present in four degrees (moving vertically in Section 3). With the hue and saturation constant, the brightness is found

to be present in three values (moving from left to right, Sections 3, 2, 1, so-called 'colors,' 'bi-hues' and 'hues'). Besides these there are 72 other colors in which brightness and saturation appear in six combinations for each of the 12 hues. In other words, in a broad sense there are present 144 colors made up of twelve hues by varying the brightness and saturation. Six of the twelve hues are made by mixture of the adjacent hues in the bottom row of large rectangles in Section 3. Each rectangle being numbered, the chart systematizes the mixture of printing inks. Such progress is commendable and highly desirable, even though empirical.

There are many other methods, but these few have been cited to show the lack of standardization of color notation and to illustrate that a system however empirical is just as desirable for the description of color as a system is for music notation. There is much yet to be done before a system of color notation is devised which will be universally adopted. First there should be some definite terms adopted descriptive of the factors influencing the quantity of a color, namely 'hue,' 'saturation,' 'brightness.' The term 'hue' is used in a more definite sense than the terms applied to the two other factors. For saturation the terms 'chroma,' 'purity,' 'intensity,' and others are being used. For brightness the terms 'luminosity,' 'value,' 'hues' or 'bi-hues,' and others are being used. Purples are often called violets or reds. These are examples of usage from which general confusion arises. The problem of color terminology does not defy solution. As a matter of fact all the quantities involved in a scientific system of notation are readily measurable. Hue, saturation, and brightness are easily determined. The available hues,

with the exception of purple, are invariable, consisting of the spectral hues. Scales of brightness (value) can be divided into any given number of parts and named in some consistent manner. The use of the terms 'high light,' 'low light,' 'medium,' 'low dark,' etc., is perhaps satisfactory, but the brightnesses that they represent should be standardized in absolute measurements in order to produce a universal scale of relative brightnesses. In fact all the terms required in a satisfactory and scientific system of color notation can be measured for their absolute values. This would reduce the systems to one basis. Such a universal system must certainly be adopted eventually, and those interested in color should put forth effort to hasten the day.

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CHAPTER V

ANALYSIS OF COLOR

25. *The Spectroscope.* — As already indicated, colors can be analyzed in various ways. The method adopted in a given case will naturally depend upon data desired. The spectroscope affords a simple means of examining colored light, but the results of the visual inspection are only qualitative. There are various designs of spectroscopes available, all based upon either the principle of the prism or of the diffraction grating (# 8 and 9). An ordinary prism spectroscope can be converted into a direct-vision instrument by combining two prisms made from different kinds of glass, so that dispersion is obtained for a certain ray without deviation. Crown and flint glasses differ in refractive index (Fig. 8), hence if prisms of each of these two glasses be made of proper refractive angles and combined so that their separate deviations practically annul each other, say, for the sodium line, dispersion is produced without deviation for this ray. Such a simple spectroscope is shown in Fig. 39. A simple diffraction grating spectroscope can be readily made, as shown in Fig. 40. A replica of a diffraction grating (# 9) is placed between two pieces of plate glass at *G*. By

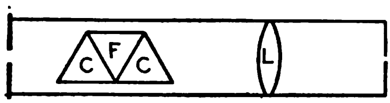

Fig. 39. — A direct-vision prism spectroscope.

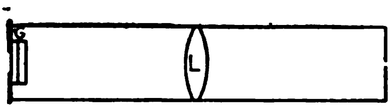

Fig. 40. — A simple grating spectroscope.

placing a lens at *L* the instrument is considerably shortened, so that it can readily be made of a pocket size. These, the simplest forms of spectroscopes, are only useful for rough qualitative analysis of the spectral character of light emitted by light sources or transmitted or reflected by colored media. A convenient form of spectroscope for qualitative analysis is the comparison spectroscope. This contains two or three distinct optical systems, so that two or three spectra may be viewed in juxtaposition. Such an instrument might be considered as roughly quantitative in its analyses, owing to the opportunity of estimating relative intensities of a given light ray in the two or three spectra.

More elaborate spectrometers will not be considered here, for the function of the spectrometer is for qualitative analysis. However, in this respect such instruments are of considerable value in color work. Photographic accessories are readily attached in place of the eyepiece. If an absorption wedge be placed before the slit, so that its transmission varies along the length of the slit, the spectrograms will roughly indicate the relative spectral distribution of energy, providing proper filters are used to allow for the variation in plate sensibility. Sometimes it is advantageous to compensate for the unequal spectral distribution of energy in the illuminant, especially in the examination of colored media.

26. *The Spectrophotometer.* — This instrument consists in principle of two spectroscopes, arranged so that the intensity of rays of the same wave-length in the two spectra can be photometrically compared. The results obtained are quantitative. A diagrammatic sketch of the optical system of a spectrophotometer is shown in Fig. 41. Light enters the

instrument from two sources at the slits S and S', respectively. At L is a Lummer-Brodhun photometer cube so constructed that through a part of the field light rays are transmitted directly from S' to the prism P and from the remainder of the field light rays from S are reflected toward the prism. After being dispersed by the prism the colored rays pass on to the eye placed at T. The wave-length of these rays depends upon the angular position of the prism which can be rotated. The photometer field is similar to that viewed in an ordinary Lummer-Brodhun photometer.

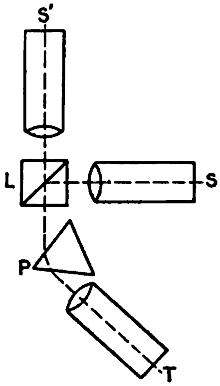

Fig. 41.—The spectrophotometer.

A small direct-vision comparison spectroscope is of considerable use in color work. Such an instrument designed by Nutting [1] contains a pair of Nicol prisms, NN, for altering the brightness of one of the spectra, as shown in Fig. 42. A right-angled

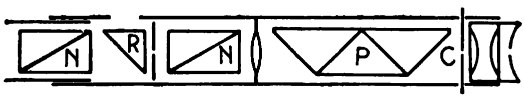

Fig. 42.—The Nutting pocket spectrophotometer.

prism, R, reflects light into the slit from one of the sources. The instrument, which is called a pocket spectrophotometer, in itself is merely for qualitative analysis. It can be set up permanently and used for quantitative measurements. However, in order to make such an instrument portable and compact, yet available for obtaining qualitative data, the author devised the attachments shown in Fig. 43. An attachment, A, containing a miniature tungsten lamp

which illuminates a ground flashed-opal glass, can be removed from its present position if desired and attached at *B*. When the comparison source in *A*

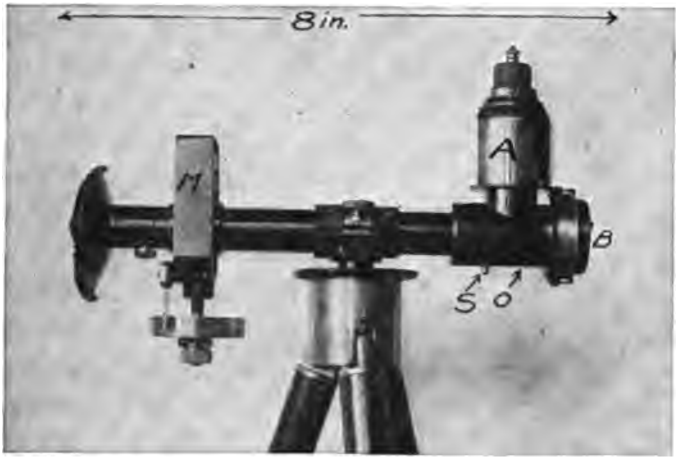

Fig. 43.—A small portable spectrophotometer for quantitative analysis.

is in the position shown the unknown source is placed at *B*. The sleeve, *O*, was placed on the instrument to support *A*. *S* controls the slit widths. A micrometer screw with a graduated scale and drum is attached at *M* to the slide containing the observing slit, *C*, which is moved across the image of the spectrum. The drum is calibrated in terms of wavelengths and the scale of the revolving Nicol prism in terms of transmission of light. The current through the lamp is obtained from a battery controlled by a rheostat and is measured by means of a small ammeter. The range of the instrument can be extended by varying the current through the lamp. This photometric field is not as satisfactory as might be desired, for it consists of two narrow bands juxtaposed at their ends. The instrument is very small,

less than 8 inches long, is mounted on a tripod, and is really portable.

There are many designs of spectrophotometers, but all have the same object. It is necessary to be able to vary the luminous intensity of one-half of the photometer field. This is done by varying the position of one of the light sources, by the use of Nicol prisms, by a neutral tint absorbing wedge, or by sectored disks. A convenient means is the variable sectored disk developed by Hyde,[2] a diagram of which is shown in Fig. 44. The disk is mounted upon a motor-driven shaft and arranged to be moved horizontally in its plane along the line *CD* in front of the slit *S*, by means of a micrometer screw. The transmission is nearly proportional to the lateral displacement.

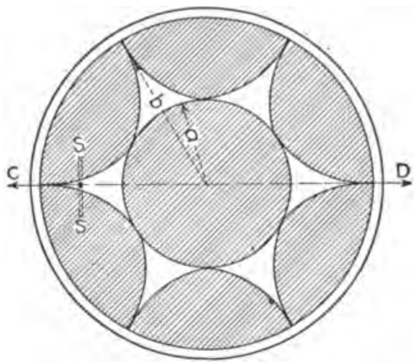

Fig. 44.—The variable sectored disk. (After Hyde.)

By means of the spectrophotometer, results can be obtained directly in terms of relative energy such as are plotted in Fig. 5 (Table II) and Figs. 122, 123. In this case the various rays in the unknown spectrum are compared directly with the corresponding rays in a spectrum of known distribution of energy. As has been previously stated the spectrophotometer is an analytical instrument, and by its use the spectral character of the light reflected or transmitted by colored media is readily obtained. An example of its use and a practical means of greatly reducing the number of readings is given below. During the

development of a glass which could be used with the tungsten lamp to produce artificial daylight [3] the procedure involved the examination of many glasses containing various proportions of coloring ingredients. A glass which proved unsatisfactory at the thickness at hand might be found satisfactory at another thickness. Therefore it was necessary to grind and polish the samples as they came from the glass factory into many different thicknesses or in the form of a wedge.

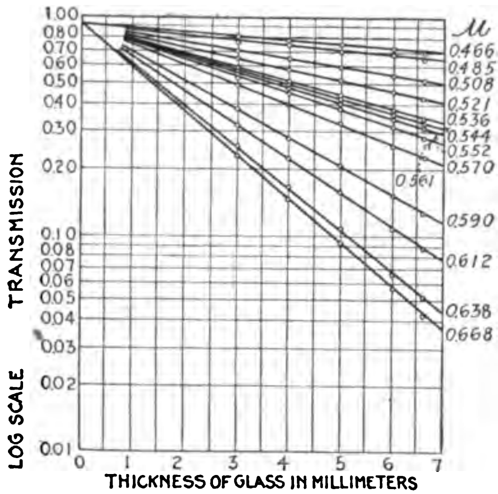

Fig. 45.—Scheme for reducing the amount of spectrophotometric work in examining transparent colored media.

This necessitated making a set of spectrophotometric readings for a considerable range of thicknesses. By utilizing the law relating transmission and thickness (density of coloring matter) of the glass, namely $I = I_0 e^{-\epsilon d}$, a simple method was devised. I_0 represents the original intensity of light of a certain wave-length and I, its intensity after traversing a thickness d of the colored glass and ϵ, the extinction coefficient. By considering the reflection from the two surfaces of the glass a relation was deduced in the form of

Log $T = \log 0.92 + kd$ (where T is the transmission, d the thickness and k a constant) which is sufficiently accurate for ordinary purposes in the spectrophotometric analysis of the transmission characteristics of colored glasses and other media. The term 'log 0.92' can be eliminated by obtaining the transmission of the colored glass in terms of a clear glass if so desired. This method necessitates an analysis of only one thickness, for, on plotting these data on logarithmic paper, as shown in Fig. 45, the data for various other thicknesses (even thicker than the sample) are readily obtained. Proof of the accuracy of this method is shown by the fact that the circles which represent data obtained on the same sample of glass at five different thicknesses lie close to the straight lines indicated by the mathematical relation expressed above. See Chapter XVII.

The spectrophotometric examination of colored media is valuable inasmuch as the eye not being analytic, other methods fail to reveal the true spectral character of the light emitted by the colored medium. This was demonstrated by the three yellows in Fig. 17 which appeared of the same hue (and practically of the same saturation), but differed greatly in spectral character.

A spectrophotometer is an elaborate and expensive instrument, therefore where the need for such an instrument is not great enough to warrant its purchase, an ordinary spectrometer with modifications can be made to serve the purpose. There are various ways of converting ordinary spectrometers into instruments satisfactory for spectrophotometric work. A double bilateral slit and a combination prism for transmitting and reflecting respectively two juxtaposed beams of light from the different sources into

the collimator is a ready means of converting a spectrometer into a spectrophotometer. However, the comparison field which consists of narrow lines juxtaposed endwise is not very satisfactory. Abney used the scheme illustrated in Fig. 46 in his early studies in color. Two slits, SS, were placed in a plane at right angles to the collimator. One slit was below the other, so that their respective images could be reflected toward the collimating lens by the two right-angled prisms which were placed one below the other. This arrangement no doubt yielded a photometric field which was not divided by an invisible line, as is desirable for high sensibility.

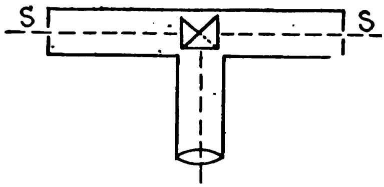

Fig. 46.—Abney's spectrophotometric attachment for a spectrometer.

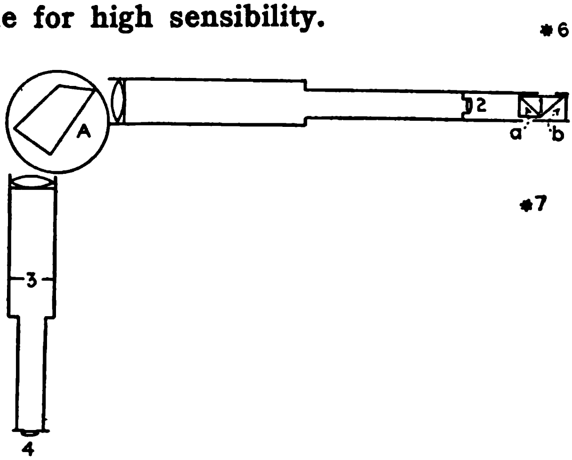

Fig. 47.—Ives' spectrophotometric attachment for a spectrometer.

A more satisfactory method is illustrated in Fig. 47. This arrangement, used by Ives,[4] was designed chiefly to avoid the errors due to instruments having two collimators becoming asymmetrical and also to avoid errors due to scattered light. At *1* in Fig.

47 is placed a combination of two right-angle prisms cemented together. The face *b* is entirely silvered and face *a* silvered halfway up. A lens at *2* forms an image in the field of the telescope tube at *3* which is observed by means of an ocular lens at *4*. The two light sources are placed at *6* and *7* respectively. A large monochromatic field is obtained which is equally affected by scattered light if any is present. Furthermore colored glasses can be judiciously used to eliminate scattered light if necessary.

A further improvement of the foregoing attachment, which was added by Nutting,[5] is illustrated in Fig. 48. The attachment consists of two reflecting prisms, P_1 and P_2, two Nicol prisms, N_1 and N_2, and a lens arranged as shown in the figure. The whole can be attached to the slit of any spectrometer. The essential factor is that a real image of the photometric field (the common surface of the two reflecting prisms) is thrown on the slit by an achromatic lens and is thus brought into the plane of the slit. The two beams of light to be compared, one passing through a portion of the photometric surface and the other being reflected by the other portion which is silvered, are brought to a brightness balance for any wave-length by rotating the Nicol prism N_1. High sensibility is claimed by Nutting for an instrument of this type.

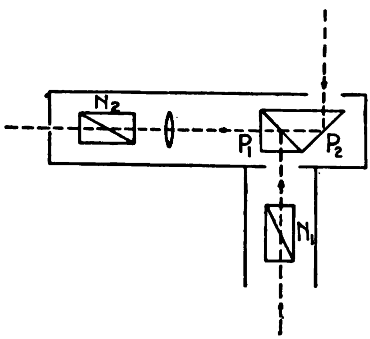

Fig. 48.—Nutting's spectrophotometric attachment for a spectrometer.

27. *The Monochromatic Colorimeter.*—Colorimeters vary in design, depending upon the data to be

obtained. In some industrial processes tintometers are employed which determine the color of substances in terms of arbitrary standards. Such instruments are colorimeters, but give no quantitative analyses of the colors. Their purpose is largely to keep the product within certain limits as to color, but they perhaps serve the purpose in many of these cases as satisfactorily as a more complex instrument. Of the instruments that analyze colors into the three terms 'hue,' 'saturation' and 'brightness,' the Nutting[6] colorimeter, being of the latest type, has been chosen for description. The optical system of this instrument, which has been called a monochromatic colorimeter, is shown in Fig. 49. Light entering the slit of collimator, *A*, which is movable, traverses the prism and is dispersed by prism *P* into its spectral components, thus furnishing the measurement of hue of the unknown light which enters through the slit of collimator C and is reflected by a portion of the diagonal surface in L, which is a Lummer-Brodhun photometer cube. White light enters the slit of collimator *B* and is reflected by the prism face and joins a portion of the beam from *A*. The eye placed at the ocular slit in *D* sees an ordinary photometric field, the two parts of which can be matched in hue, saturation, and brightness. The hue is matched by varying the angular position of *A* and the saturation by varying the amount of white light added. The amounts of light entering the slits can be varied by changing the slit widths, by rotating sectors, or by rotating one of a pair of

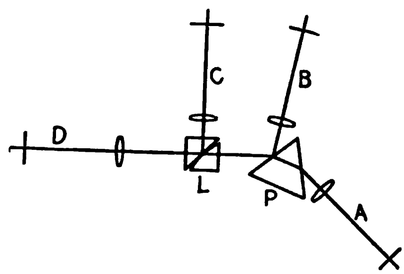

Fig. 49.—The Nutting monochromatic colorimeter.

Nicol prisms placed just inside the slits. In analyzing a purple, for which no spectral match in hue exists, a spectral color is mixed with the unknown, the remaining procedure being obvious. The later instruments have been altered somewhat in construction, but the principle remains the same. The accuracy with which the dominant hue is obtainable is claimed to be about .001 to .002μ except in the extreme regions of the spectrum, for very unsaturated colors and dark shades. Data obtained by Nutting [6] are given in Table V.

TABLE V

Materials	Hue	Per cent white	Reflection coefficient
Sulphur	0.571μ	48	0.80
Cork	.586	56	.26
Dandelion	.580	9	
Tobacco leaf (medium)	.597	65	.14
Chocolate	.595	70	.05
Butter, light	.580	45	
Butter, dark	.580	28	.64
Navy blue (U. S.)	.472	90	.019
Paris green	.511	56	.386
Manila paper	.582	65	.57
Copper	.597	70	.23
Brass, light	.575	60	.32
Brass, dark	.583	61	.25
Gold, medium	.591	64	.21

Data obtained by Abney [7] in the analysis of the color of glasses and pigments are presented in Table VI.

In Table VII are given some data on the color of illuminants obtained by L. A. Jones [8] with the monochromatic colorimeter.

TABLE VI

Glasses	Hue	Saturation	Brightness
	Dominant hue	Per cent white	Transmission coefficient
Ruby	0.622μ	2	0.131
Canary	.585	26	.820
Bottle-green	.551	31	.106
Signal-green	.4925	32	.069
" "	.510	61	.194
Cobalt	.4675	42	.038
Pigments	**Dominant hue**	**Per cent white**	**Reflection coefficient**
Vermillion	0.610μ	2.5	0.148
Emerald-green	.522	59	.227
French ultramarine blue	.472	61	.044
Brown paper	.594	50	.25
Orange	.5915	4	.625
Chrome-yellow	.5835	26	.777
Blue-green	.5005	42.5	.148
Eosine dye	.640	72	.447
Cobalt-blue	.482	55.5	.145

TABLE VII

Source	Per cent white	Hue
Sunlight	100	....
Average clear sky	60	0.472μ
Standard candle	13	.593
Hefner lamp	14	.593
Pentane lamp	15	.592
Tungsten glow lamp, 1.25 w. p. c.	35	.588
Carbon glow lamp, 3.8 w. p. c.	25	.5915
Nernst glower, 1.5 w. p. c.	31	.5867
Nitrogen-filled tungsten lamp, 1.00 w. p. m. h. c.	34	.586
Nitrogen-filled tungsten lamp, 0.5 w. p. m. h. c.	45	.5845
Nitrogen-filled tungsten lamp, 0.35 w. p. m. h. c.	53	.584
Mercury vapor arc	70	.490
Helium tube	32	.598
Neon tube	6	.605
Crater of carbon arc at 1.8 amperes	59	.5846
Crater of carbon arc at 3.2 amperes	62	.5846
Crater of carbon arc at 5.0 amperes	67	.5834
Acetylene flame (flat)	36	.5855

In colorimetric work a standard white light is necessary. Jones used noon sunlight, which he found to be constant in color from 9 A.M. to 3 P.M., the observations extending over several weeks. This light was reflected into the instrument from a magnesium carbonate block.

Many interesting studies in color-mixture can be made with such a colorimeter. An example is found in the work of L. A. Jones [9] in the analysis of mixtures of two component colors. Filters were chosen in several cases practically complementary in color. These filters were in the form of sectors of a circle and of equal angular extent. An opaque sector equal in size to one of the filters was varied in position over the sectors, so that they could be left open in any desired proportions. Lights passing through these filters were mixed in a complete range of ratios and the resultant mixtures were examined by means of a monochromatic colorimeter for hue and saturation or per cent white. For example, we will choose one of the pairs of filters, a red and blue-green of dominant hues 0.624μ and 0.497μ respectively. The saturation or purity of the colors are indicated by the per cent of white light (noon sunlight) that each transmitted, these being for the red and blue-green filters respectively 3.3% and 28%. The transmission coefficients of the two filters were respectively 24% and 16%. The data obtained in analyzing various mixtures of the two colored lights are shown in Fig. 50. It is seen that practically only two hues are obtained in a complete range of mixtures and these are the dominant hues of the respective colored lights. The dominant hue of the mixtures changes abruptly from the hue of one of the colored lights to that of the other at the point

near where the mixture contains the maximum amount of white light, or in other words where the two lights are nearest to being complementary. The per cent white reaches a maximum of 95% (indicating that the colored lights are here practically complementary) when the blue-green filter was open about 62% and the red filter about 38%. A conclusion, among others drawn by Jones from this in-

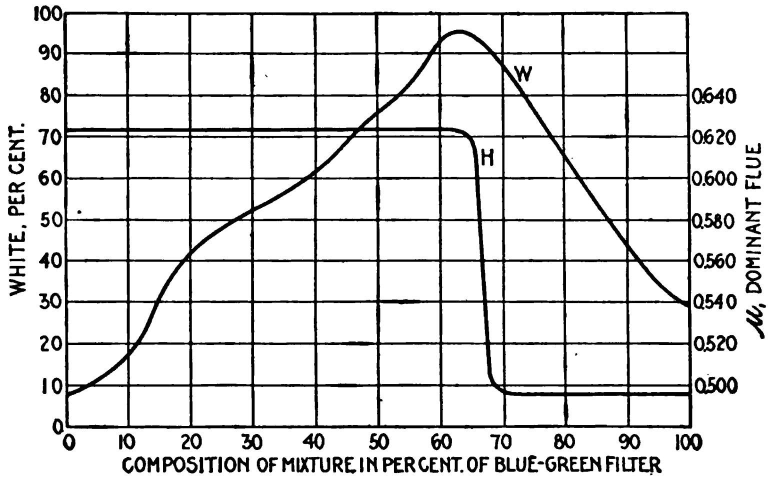

Fig. 50.—Analysis of two-component color-mixtures.

vestigation, is that it is not possible with two filters that are complementary or nearly so to produce mixtures that show appreciable color of more than two dominant hues, these hues being the dominant hues of the two components of the mixture. He points out other possibilities for this colorimeter in investigations in color-mixture.

The author has used an arrangement diagrammatically shown in Fig. 51 for the study of various problems, chiefly that of the influence of saturation of color in heterochromatic photometry. This arrangement has all the essentials of a colorimeter for

analyzing colors into hue, saturation, and brightness. Light from a source *L* emitting light of a continuous spectrum enters the collimator of a Hilger spectroscope and is dispersed by the prism. A standard white light illuminates the non-selective ground opal glass, *O*, an image of which is reflected into the objective telescope from the prism face as shown. A white sectored disk, *D*, which is smoked with magnesium oxide by holding near a burning magnesium ribbon, is placed so that it bisects the field,

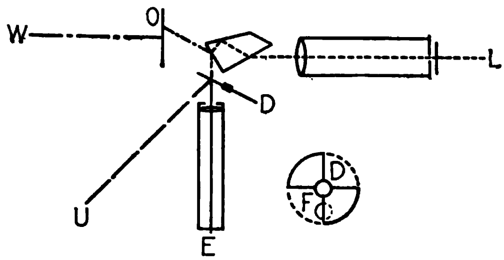

Fig. 51.—A simple method of converting a spectrometer into a combined monochromatic colorimeter, direct comparison photometer, flicker photometer, and spectrophotometer.

F, vertically. If the edges of the sectors are beveled and well sharpened, the dividing line can be made to disappear almost completely. The light from the unknown, *U*, is reflected from the disk. By varying the intensity of the various lights the desired measurements can be made. The hue is determined by the position of the wave-length drum; the amount of white light can be measured by comparing with a standard at *U* or by a previous calibration. The brightness can be measured either by the direct comparison or the flicker method of photometry (# 55). The sectored disk provided with a motor drive is in reality a Whitman-disk flicker photometer. As already stated the arrangement was originally devised for another investigation; however, it readily serves

the requirements of a monochromatic colorimeter. Transparent colored media can be illuminated by a standard white light placed at *U*. Likewise opaque colored media can be placed on the disk *D* and illuminated by a white light.

28. *The Tri-color Method.* — It is well known that any color can be matched in hue by mixing the three primary colors, red, green, and blue, in proper proportions. The Young-Helmholtz theory of color visiön is largely based on this experimental fact (#47). Köenig found, by a rather complex method, the relative amounts of the three primary color sensations aroused by the various spectral colors and determined

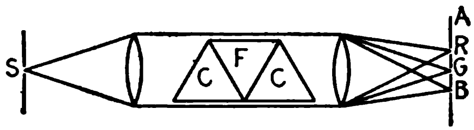

Fig. 52. — Illustrating the principle of the Maxwell 'color box.'

the so-called sensation curves of the eye (Fig. 54). Maxwell was one of the first to obtain quantitative data in matching colors by a mixture of three primary spectral colors. His apparatus, known as the 'color box,' though somewhat more complex, involved the fundamental principle shown in Fig. 52, and is based upon the fact that an optical path is 'reversible.' For example if a spectrum is formed at *A* by means of a collimator and a prism by light entering the slit, *S*, of the collimator and traversing a prism, we can obtain a patch of light of any color by placing slits, *R*, *G*, and *B*, in the spectrum and combining the light from these on a distant screen. Conversely, if the latter slits be illuminated with white light on looking into the collimator slit, *S*, the prism face will appear of a color which is the result of the mixture of the colors of the slits which, in the first case, were

combined by means of a lens into one colored patch on the distant screen. Hence, instead of forming a spectrum at *A*, and producing colored light by mixtures of *R*, *G*, and *B*, by slits placed at these points and combining the three colored lights, Maxwell adopted the reverse process. He illuminated the three slits by sunlight reflected from a white diffusing surface placed in front of them, and on looking into the slit, *S*, he saw the prism face appear in colors corresponding to the positions and proportions of *R*, *G*, and *B*. This composite color he compared with the original white light or any colored light. The Maxwell color box was actually constructed in a different manner, but the principles involved are the same as indicated above. By means of this instrument he obtained many color equations of the form $xR + yG + zB = C$. By a similar method Köenig obtained data which resulted in the production of the so-called sensation curves of the eye. Abney has employed the method in a great deal of work in color analysis, including the study of color vision, the analysis of pigment colors, and of the color of illuminants.

A colorimeter based upon the tri-color method of analysis was developed by F. E. Ives.[10] Instead of spectral colors, red, green, and blue colored filters are employed in this instrument, which is illustrated in Fig. 53. By means of this instrument colors are analyzed in terms of the colors of the filters *R*, *G*, and *B*. These can be reduced to sensation values as shown later. *D* is a variable slit which is illuminated by light of the color to be analyzed and *A* is an optical mixing wheel consisting of twelve convex lenses arranged to rotate. By means of this wheel the various amounts of the red, green, and blue components are mixed to match the light from *D*. *F*

is the field lens and *C* a prism or small angle which divides the photometric field by a sharp line in the middle. *H* is the eyepiece, *J* is a hinged front carrying the objective lens, *K*, and prismatic lens *L*. These are unnecessary for some work and can be replaced by a non-selective ground opal glass. The procedure in making observations with this

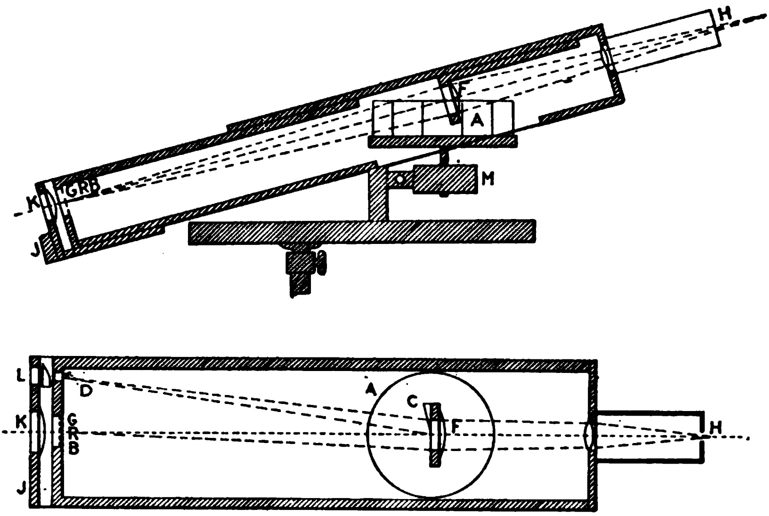

Fig. 53.—The F. E. Ives colorimeter.

instrument is obvious. If the colorimeter readings which are obtained from the position of the levers which control the slit widths of *R*, *G*, and *B*, be reduced to sensation values they become much more valuable. H. E. Ives [11] has done this in analyzing the color of illuminants, by using the sensation curves obtained by Köenig and modified by Exner. These are shown in Fig. 54. They are based upon experimental data which has afforded strong confirmation of the Young-Helmholtz theory of color vision which assumes three fundamental color sensations are responsible by different degrees of excitation for

the perception of all colors (#47). It is noted that each of the three supposed primary color sensations

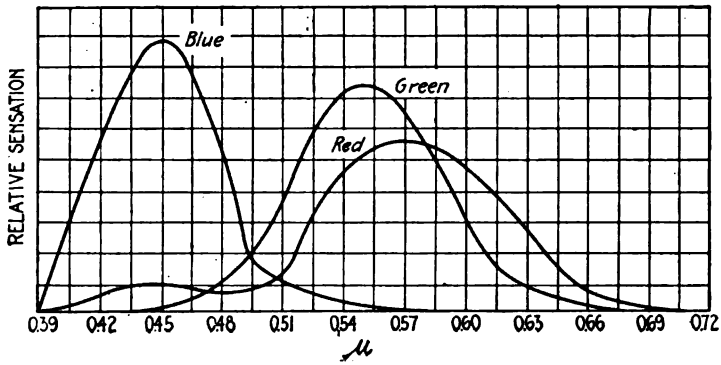

Fig. 54.—Kŏenig's sensation curves.

is not excited by a limited portion of the spectrum. In fact, spectral rays in general are supposed to

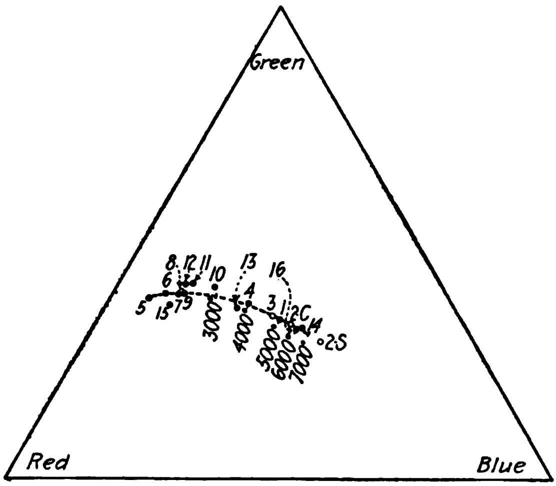

Fig. 55.—Tri-color colorimeter measurements.

excite the sensations in relatively different degrees, depending upon the wave-length. After a preliminary investigation Ives concludes that these curves are a much nearer approach to the truth than those obtained by Abney. In reducing the colorimeter

readings to sensation values it was necessary to obtain the red, green, and blue sensation values of the colorimeter screens. Spectrophotometric analysis of the screens combined with the data in Fig. 54 yield the primary sensation values of the screens which are obtained in relative values by integrating the areas under the sensation curves for the three screens and reducing the colorimeter readings accordingly. Each of the three colorimeter readings represents a mixture of the three primary sensations, depending upon the primary sensation values of the colorimeter screens. The procedure is simple but more details, if desired, can be obtained from the original paper. The primary sensation values of various illuminants compared with average daylight as determined by Ives are found in Table VIII, some of which are plotted in Fig. 55. The data represent

TABLE VIII

Color of Illuminants by Tri-chromatic Colorimeter (See Fig. 55)

Source	Sensation values		
	Red	Green	Blue
1. Black body 5000° abs.	33.3	33.3	33.3
2. Blue sky (S)	26.8	27.2	46.0
Blue sky (C)	32.0	32.0	35.8
3. Overcast sky	34.6	33.9	31.5
4. Afternoon sun	37.7	37.3	25.0
5. Hefner lamp	54.3	39.5	6.2
6. Carbon incandescent lamp, 3.1 w. p. m. h. c.	51.1	40.5	5.4
7. Acetylene	48.6	40.8	10.6
8. Tungsten incandescent lamp, 1.25 w. p. m. h. c.	48.3	40.8	10.9
9. Nernst	49.2	40.7	11.1
10. Welsbach, $\frac{1}{4}$% cerium	42.5	40.8	16.7
11. Welsbach, $\frac{3}{4}$% cerium	45.4	42.0	12.6
12. Welsbach, $1\frac{1}{4}$% cerium	47.2	41.8	11.0
13. D. C. Arc	41.0	36.3	22.7
14. Mercury arc	29.0	30.3	40.7
15. Yellow Flame arc	52.0	37.5	10.5
16. Moore carbon-dioxide tube	31.3	31.0	37.7

the means of the values determined by two methods, namely colorimeter readings and likewise spectrophotometric data reduced to sensation values. (The primary color sensation values of the spectral colors and principal lines of the cadmium and mercury spectra are plotted in Fig. 31.) The dotted line represents the color of a black body (or an incandescent solid emitting radiation non-selectively) for temperatures between 3000 and 7000 degrees absolute (*C*). Most of the artificial illuminants lie along this curve. Those radiating selectively in the visible spectrum, such as the yellow flame arc and Welsbach mantle, do not lie upon it. Ives concludes that the spectral distribution of energy in noon sunlight which reaches the earth's surface is quite similar to that of the black body at 5000 degrees absolute (*C*) as computed from radiation laws (# 6).

Another instrument for tri-color analysis which is extremely simple is illustrated in Fig. 56. This method, which has been applied by many in various color investigations, has been used by Bloch.[12] A disk containing four circular apertures, three being respectively covered by red, green, and blue screens, is pivoted so that the various screens can be brought before the ocular aperture in a photometer head. Photometric balances are made while viewing the field through the various filters separately and the results are plotted on rectangular coördinates, the ratio of red to green intensities being plotted against the ratio of blue to green intensities. Bloch presents

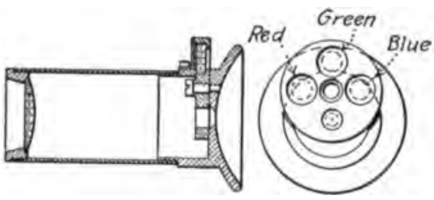

Fig. 56.—Arrangement for using color filters before a photometer eyepiece.

plats containing his color analysis of many illuminants and the spectrophotometric analyses of the filters are also shown. Such results can hardly be considered more than approximately comparative and of limited usefulness. In general, data concerning the color of illuminants or of colored media obtained by the tri-color method of analysis are limited in usefulness, owing to the fact that the method is not sufficiently analytical. The usefulness of such a method is broader than the tintometer with its arbitrary standards of color, but the spectrophotometer and monochromatic colorimeter as a rule yield more useful data, the former being quite analytical for spectral examination and the latter rendering data in terms of the specific qualities of a color, namely, hue, saturation, and brightness.

29. *Other Methods of Color Analysis.* — Many instruments have been devised for color analysis based on principles differing from the foregoing. A number of colorimeters employing colored solutions have been used, the measurements usually being made in terms of the depth of liquids of certain concentrations. Purple and green solutions have been used by Fabry for eliminating color difference in photometry. In a sense such a procedure is a colorimetric method if it is desired to use it as such. The Kirchoff-Bunsen and Stammer colorimeters employ colored solutions for the measurement of color.

Leo Arons [13] has devised a colorimeter based upon the rotation of the plane of polarization by quartz plates (#11) which have been cut perpendicularly to their crystallographic axes. This instrument is illustrated in *I*, Fig. 57. White light from a diffusely reflecting porcelain disk is reflected into the instrument through a circular hole, *B*, and is rendered

plane-polarized by the Nicol prism, *P*. A quartz plate at *Q* rotates the plane of polarization of various rays through various angles depending upon the wave-length. The beam then passes through another Nicol prism, *A*, thence through the central portion of the Lummer-Brodhun photometer cube, *W*, and to the eye beyond *R*. The eye sees a circular patch of light of a certain color depending upon the thickness of the quartz plate and the relative angular positions of the Nicol prisms. This colored patch is

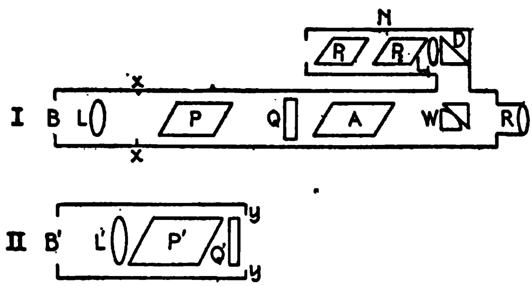

Fig. 57.—Arons colorimeter.

matched in color with the light entering the side tube, *N*. The latter beam is controlled in intensity by the two Nicol prisms, P_1 and P_2, and is reflected by the totally reflecting prism, *D*, to the photometer cube, which in turn reflects the light to the eye in a beam concentric with the first beam. The colored media are placed in front of tube *N*, and are preferably illuminated by the same source that illuminates the porcelain disk in front of *B*. Mixed colors are obtained, the Nicol, *A*, subtracting certain rays depending upon its angular position leaving the remaining light colored instead of white. Six quartz plates are provided, of thicknesses 0.25, 0.5, 1.0, 2, 4, and 8 millimeters respectively, which are mounted in brass plates. These plates have two identical

holes, one covered with the quartz plate, the other unobstructed. These are arranged to slide in or out of the instrument at or near *Q*. By sliding any of the brass plates to the side any number of quartz plates can be arranged one after another and thus the total thickness of quartz in the path of the beam from *B* can be adjusted in steps of 0.25 mm. to a total thickness of 15.75 mm. A still greater variety of colors can be obtained by using two sets of Nicol prisms and quartz plates in series. Therefore the tube in *I* can be removed at the plane *xx*, and tube *II* connected at the end *yy*. B′ takes the place of *B* and lens *L′* the place of *L*. Any thickness of quartz plates at *Q′* can be inserted; however, only a single plate is employed by Arons, this one being 3.75 mm. in thickness. In case transparent colored media are to be examined, a white diffusely reflecting porcelain disk similar to the other one is used in front of the tube *N*. The two disks should receive the same intensity of illumination from the same source. If opaque colors are to be examined for reflection, these are placed on the porcelain disk, and the observer sees an outer ring through *R* of the color of the unknown. This is matched in color and brightness by adjusting the thickness of quartz and the angular position of the Nicol prisms until the inner circle appears of the same color and brightness as the outer ring. The measurements are recorded in terms of the thickness of quartz, the angle between *A* and *P* and the angle between P_1 and P_2 and also between *P′* and *P* if the tube II is in use.

30. *Templates.* — Much of the early investigation in color was done with the rotating disks (Fig. 23) and it is quite natural that modifications of these would be made. Abney devised an ingenious method

for showing the effect upon the color of the integral light of various spectral energy distributions and also of showing that a certain determined spectrophotometric curve was in reality the analysis of an integral color. On determining the relative amounts of light of various wave-lengths reflected by a pigment these, instead of being plotted on rectangular coördinates as shown by the dotted lines in Fig. 12, were plotted in a special manner on a disk. Along a portion, *VR*, of a radius of the circle in Fig. 58, a wave-length scale is laid off. The relative amounts of light of different wave-lengths reflected from the pigment as determined by means of a spectrophotometer are laid off on circumferences of circles concentric with the center of the disk starting at a certain point of *VR* corresponding to the wave-length. The cardboard is now cut out along the boundary line, the template in Fig. 58 being Abney's template for carmine. If this disk be carefully adjusted in the plane of a spectrum formed in space so that various wave-lengths along *VR* coincide with corresponding wave-lengths in the spectrum and the disk be rotated, on combining the colored rays passing through the rotating aperture upon a white screen by means of a lens the color of the integral light reflected from carmine is seen. This patch will be exactly like the original color in appearance providing the optical parts of the instruments are non-selective and the same light is used in producing the spectrum as was used in illuminating the pigment when the spectrophotometric observations were made. Of course the irrational dispersion of the prism must be properly allowed for and the spectrum must be narrow.

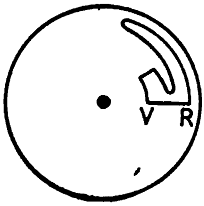

Fig. 58.—Abney's template for carmine.

Instead of rotating the template before an actual spectrum Abney used the principle adopted by Maxwell in his 'color box' (Fig. 52), thus rotating the disk before a long narrow slit illuminated by the total light from the illuminant. The integral color was viewed through the eyepiece of the spectrometer. Abney made a number of these templates representing pigments, illuminants, and the luminosity curve of the eye.

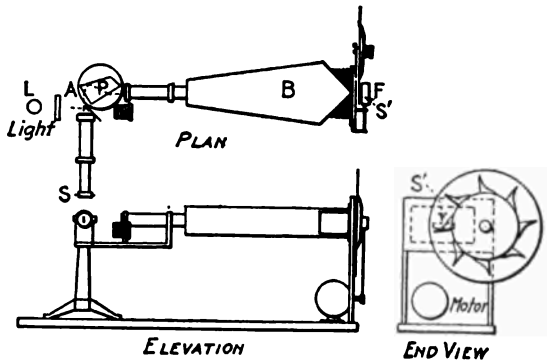

Fig. 59.—Adaptation of Abney's scheme for the spectroscopic synthesis of color.

Recently Ives and Brady [14] applied Abney's principle to the alteration of the light from a 4 w.p.m.h.c. carbon lamp to that of 'average daylight' and also to that from the blue sky. A Hilger constant-deviation spectrometer was used, as shown in Fig. 59. The regular camera attachment *B* was placed in the position ordinarily occupied by the collimator, the latter being placed in the position of the objective telescope. The slit at *S* is long and narrow and is illuminated by light from the carbon incandescent lamp reflected from a white surface at *F*, the principle being the same as just presented in the description of Abney's work on templates. These templates were computed on the assumption that the

relative spectral energy distribution in the spectrum of the carbon incandescent lamp operating at 4 watts per mean horizontal candle is that derived from the Wien equation (equation 2, #6) for a black body at a temperature of 2080 deg. absolute (*C*), and that of white light corresponding to a temperature of 5000 deg. absolute. The templates for converting the carbon light into blue sky light were made from relative spectrophotometric measurements. The disk in position is shown in the three views of the apparatus taken from the work cited above. The advantage of using the templates before a slit illuminated by white light is that a much greater amount of light is available than in the case of using it before a spectrum and recombining the transmitted light by means of a lens. A comparison field can be arranged by reflecting the light *L* into the instrument as shown. Abney cut a template corresponding to the luminosity curve of the eye which is of interest, but owing to the work of various modern investigators this has been more accurately established. The template scheme can be applied by using disks in which openings are cut corresponding to the luminosity curve of the eye and replacing the surface at *F* before the objective slit by a straight incandescent filament; thus the transmissions of absorbing media can be determined by pure energy measurements.

31. *The Nutting Reflectometer.* — In the study of color it is sometimes desirable to ascertain the reflection coefficients of colored media. This can be done if the object is diffusely reflecting by means of an ordinary brightness photometer, although the uncertainties of color photometry will be present in any case. However, Nutting[15] has devised a simple instru-

ment shown in Fig. 60 that is very useful for determining the reflection coefficients of any colored media for light incident from all possible directions simultaneously. Two crown glass prisms of 21 deg. angle are fastened over the two apertures in the end of a Köenig-Martens polarization photometer and the latter is inserted into a metal ring which is nickel-plated and polished inside. The light enters the apertures of the instrument along the dotted lines shown and is divided into two plane-polarized beams by a Wollaston prism. These beams can be balanced in intensity by rotating the Nicol prism. The surface whose reflection coefficient is desired is placed on one side of the ring completely covering it and this is illuminated by a non-selective ground opal glass on the other side of the ring. The instrument is placed upon a wooden frame for convenience. The light is reflected back and forth between two planes of 'infinite' extent made practically so by the polished ring. Simple theory shows that the ratio of the brightness of the unknown to that of the ground opal glass is a direct measure of the reflection coefficient of the former for the character of the illumination it receives. Certain precautions must be taken into consideration as explained by Nutting.

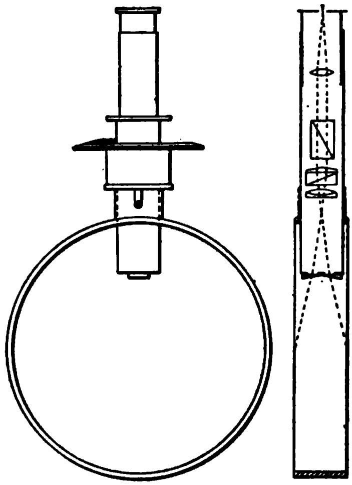

Fig. 60. — The Nutting reflectometer.

32. *Methods of Altering Brightness of Colors Non-selectively.* — It is often desirable to alter the

brightness of colored lights without altering them spectrally. A simple means is found in varying the distance of the light source and computing the relative intensities from the 'inverse square law.' However, sometimes this is inconvenient. Sectored disks are often resorted to with satisfactory results. These are now being used in photometry to a great extent, the variable sectored disk devised by Hyde (Fig. 44) being especially convenient and reliable for spectrophotometry. The Brodhun variable sector is another device very often applicable. In this instrument a beam of light is rotated and is controlled in intensity by a variable stationary sector. Plate glass varied in its angular position with respect to the axis of the beam affords a means of obtaining a slight range of brightnesses, although non-selective glass is rarely found. Wire mesh and grids thoroughly blackened are satisfactory in some problems. Neutral tint wedges have been used, but it is difficult to obtain strictly non-selective smoke glass. Ives and Luckiesh [16] studied the transmission characteristics of half-tone gratings (black lines on clear glass) and found them to be satisfactory if properly used. Photographic screens are found to serve some purposes, but they must always be calibrated in position owing to their tendency to diffusely reflect light. These are a few methods which have proved helpful in the proper place.

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CHAPTER VI

COLOR AND VISION

33. *The Eye.* — Color vision is not essential, because achromatic vision serves the totally color-blind person well. However, the ability to perceive colors extends the usefulness of the sense of sight very much. It not only adds greatly to our pleasure but is utilized in many ways. The eye can be considered optically as a rather simple instrument, as indicated by the photograph of the middle vertical section of a human eye shown in Fig. 61. It is seen that the refracting media consist of the cornea, aqueous humor, lens, and vitreous humor. The retina, which consists of the optic nerve spread out over the interior of the eyeball, is a very thin membrane, and can be seen in the illustration partially detached from the wall. The radii of curvature, thickness, and refractive index of the various eye media as determined by Helmholtz [1] are given in Table IX. The normal eye, while being a wonderfully adaptable instrument, is not free from errors, owing to the fact that it is optically quite simple. The chief error of interest here is its lack of achromatism. If an image of an object illuminated by light having a continuous spectrum be produced by a simple lens

Fig. 61. — A vertical section of the human eye.

TABLE IX

Optical Constants of the Eye

	Distant vision	Near vision (15 cm.)
Index of refraction of the humors and cornea..........	1.3365	
Index of refraction of the crystalline lens..............	1.4371	
Effective index of refraction of lens surrounded by humors	1.0753	
Radius of outer surface of cornea	7.8 mm.	7.8 mm.
Radius of first lens surface..........................	10.0	6.0
Radius of second lens surface	6.0	5.5
Thickness of cornea..................................	0.4	0.4
Thickness of crystalline lens.........................	3.6	4.0
Distance of first lens surface from cornea	3.6	3.2
Distance of second lens surface from cornea...........	7.2	7.2

it will be found to have a red, blue, or purple fringe. This is readily understood from Fig. 62, which represents a schematic eye in which only the simple lens is considered. Owing to the difference in the refractive index of a medium for rays of different wave-length, such a result as is exaggerated in Fig. 62 will obtain. The refractive index being greater for rays of shorter wave-length, the blue rays will be deviated or refracted more than the yellow rays, and the latter more than the red rays. Naturally the eye focuses for the brightest rays, which in ordinary light are the yellow-green or yellow rays. Therefore, the blue and red rays will be out of focus, with the result that the image of the point, *P*, will be surrounded by a purple fringe. This is of importance in vision, as will be shown later. The lack of achromatism of the eye can be demonstrated very simply. On viewing, by reflected light, the concentric circles shown at the right of Fig. 62 held close to the eye they appear colored. A very striking experiment is found in focusing a line spectrum — that of mercury will suffice — upon a ground glass. On

viewing it at a normal distance (14 inches), the yellow and green lines will appear sharply focused, but the blue and violet lines will appear hazy and quite out of focus. On bringing the eye closer the latter lines will begin to appear clearer, and finally, when the eye is within about six inches of them, they will still appear clear-cut, while it will be quite impossible to accommodate the eye sufficiently to focus the yellow and green lines. In other words the eye is near-sighted (myopic) for blue rays and far-sighted (hyperopic) for red rays. On viewing a narrow continuous spectrum at some distance the blue end appears to

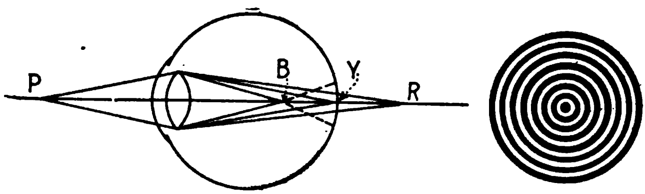

Fig. 62.—Showing the effect of chromatic aberration in the eye.

flare out. Another simple demonstration is found in viewing an illuminated slit through a dense cobalt glass which transmits extreme red and violet rays. On accommodating the eye for a point behind the slit a red image with a violet halo is seen. On accommodating for a point in front of the slit a violet image with a red halo is seen. This defect plays a prominent, though usually unnoticed, part in vision. A lens can be made practically achromatic by combining a convergent lens of crown glass with a divergent lens of flint glass. The former is more strongly convergent for blue than for red rays, while the latter is more strongly divergent for blue than for red lights. It is thus possible to bring the red and blue rays in coincidence at a focus. Inasmuch as it is only possible to bring two rays exactly into coincidence by

a two-piece lens, such a lens is not truly achromatic, though practically so for most purposes. By combining more lenses the approach to true achromatism is brought as near as desired. A simple achromatic lens is illustrated in Fig. 63.

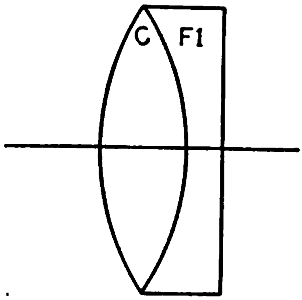

Fig. 63.—A simple achromatic lens.

The retina has been found to vary in its sensibility to colors. The central region is sometimes known as the yellow spot, because it apparently absorbs the violet and blue rays to a greater degree than other rays. The effect of the yellow spot is often seen in viewing colors one after another, and it is quite noticeable at twilight illumination. It appears of somewhat irregular outline in after-images. Studies of the various zones of the retina as to their sensibility to various colors yield results in general similar to those shown in Fig. 64. The center of the fovea corresponds to the center of the circle. The solid line shows the boundary for the perception of light. The visual field for one eye extends outward about 90 deg. from the normal optical axis of the eye, inward about 60 deg., downward 70 deg., and upward 50 deg. The dashed line represents the extreme limits where blue can be perceived as such and the remaining two lines represent respectively the limits for red and green perception. These facts must be reconciled with any satisfactory theory of vision. It might be noted here that each eye has a blind spot — the point of entrance of the optic nerve—which is totally insensitive to light. The retina, which consists of the optic nerve spread out, is covered with a mass of microscopic 'rods' and

'cones' (#48) projecting outward toward the lining of the eyeball which play an important part in theories of vision.

34. *Brightness Sensibility.* — The sensibility of the retina to brightness differences is greatest over a wide range of intensities, falling off at extremely

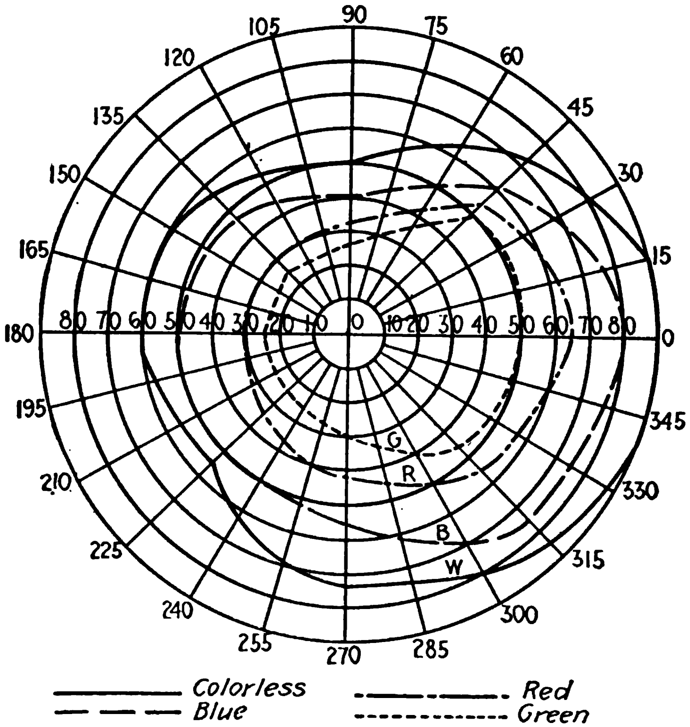

Fig. 64. — Limits of the visual field for colored and colorless lights.

low and extremely high brightnesses. With decreasing intensities the sensibility diminishes more rapidly for rays of longer wave-length than for those of shorter wave-length. Köenig and Brodhun [2] have done excellent work in this field as well as in many other fields pertaining to vision. They determined the least perceptible brightness increment for lights

of various colors including white, for brightnesses of a neutral tint surface ('white') illuminated to various intensities from 1,000,000 meter-candles to nearly the

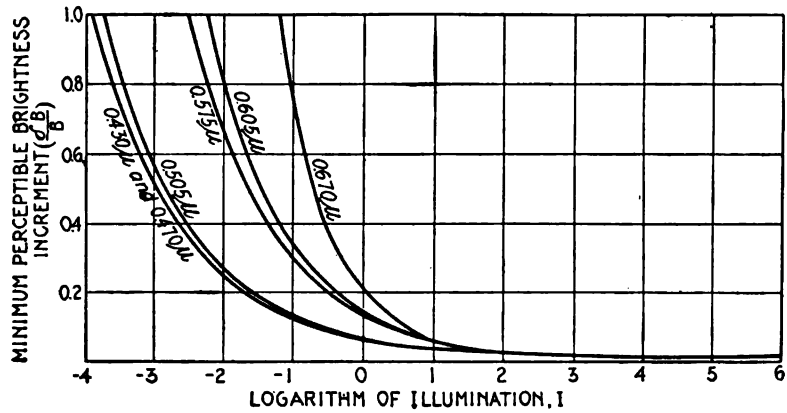

Fig. 65.—Brightness sensibility data. (See Table X.)

threshold of vision, using an artificial pupil of 1 sq. mm. area. They started at 600 meter-candles and extended the illumination above and below by the various steps indicated in the accompanying table. The data for Köenig's eye after modification by Nutting[3] are shown in Fig. 65 and Table X. Köenig and Brodhun did not include the increment (δB) in the total brightness (B) in calculating the values $\delta B/B$. Nutting recomputed the data with the threshold value included. It is seen that the increment of brightness difference just perceptible, increases as the brightness decreases and more rapidly for the rays of longer wave-length. At high illuminations the minimal perceptible increment is about the same (1.6%) for all colors, including white. For the ordinary range of brightnesses $\delta B/B$, is constant, which fact is known as Fechner's law, and the constant is called Fechner's coefficient.

TABLE X

Data of Köenig and Brodhun on Brightness Sensibility as Recalculated by Nutting

Wave-length =	0.670μ	0.605μ	0.575μ	0.505μ	0.470μ	0.430μ
B_0 =	0.060	0.0056	0.0029	0.00017	0.00012	0.00012
Meter Candles	$\frac{\delta B}{B}$					
200,000	......	0.0425	......	......	......	......
100,000	......	0.0241	0.0325	......	......	......
50,000	0.0210	0.0255	0.0260	......	......	......
20,000	0.0160	0.0183	0.0205	0.0195	......	......
10,000	0.0156	0.0163	0.0179	0.0181	......	......
5,000	0.0176	0.0158	0.0166	0.0160	......	......
2,000	0.0165	0.0180	0.0180	0.0175	0.0180	......
1,000	0.0169	0.0198	0.0185	0.0184	0.0167	0.0178
500	0.0202	0.0235	0.0180	0.0194	0.0184	0.0214
200	0.0220	0.0225	0.0225	0.0220	0.0215	0.0245
100	0.0292	0.0278	0.0269	0.0244	0.0225	0.0246
50	0.0376	0.0378	0.0320	0.0252	0.0250	0.0272
20	0.0445	0.0460	0.0385	0.0295	0.0320	0.0345
10	0.0655	0.0610	0.0582	0.0362	0.0372	0.0396
5	0.0918	0.103	0.0888	0.0488	0.0464	0.0494
2	0.1710	0.167	0.136	0.0655	0.0715	0.0600
1	0.258	0.212	0.170	0.0804	0.0881	0.0740
0.5	0.376	0.276	0.208	0.0910	0.096	0.0966
0.2	......	0.332	0.268	0.110	0.127	0.116
0.10	......	......	0.396	0.133	0.138	0.137
0.05	......	......	......	0.183	0.185	0.154
0.02	......	......	......	0.251	0.209	0.223
0.01	......	......	......	0.271	0.189	0.249
0.005	......	......	......	0.325	0.300	0.312
0.002	......	......	......	......	......	0.369

The value of the minimal perceptible increment depends largely upon the method of making the measurements. Usually the brightness of one of the two parts of the photometric field is varied until it appears just perceptibly brighter or darker than the comparison field. This procedure yields values of

the least perceptible increment comparable with the foregoing value. In precision photometry the accuracy is often as high as 0.1 per cent; however, another factor enters into such procedure. The brightness of one part of the field is varied between certain limits at which it is respectively distinctly brighter and darker than the comparison field, and these limits are gradually brought nearer together until finally an attempt is made to estimate the middle point. This cannot be considered a measure of brightness sensibility. However, P. W. Cobb has employed a method which is of considerable interest here inasmuch as he obtains values for the minimal perceptible increment for white light smaller than 0.5 per cent. In these experiments the test field was exposed to the view of the observer for a brief, but constant, period, after which his judgment was recorded. One side of the field appeared either brighter or darker, or no difference in brightness was distinguishable. This procedure was repeated for a range of aspects of the test field varying from that in which one side appeared distinctly darker for a number of successive exposures to that in which it appeared definitely brighter. Obviously, by progressing in small steps between these two limits (presenting these various aspects in haphazard order) there were several near equality where the judgment was uncertain. After reducing the data by a special method Cobb concludes that the minimal perceptible increment is much smaller than that obtained by Köenig and Brodhun.

The data of Köenig and Brodhun has been extended by Nutting by computation to the point where $\delta B/B = 1$; that is, to the threshold value. This computation is very interesting, though perhaps not

entirely free from criticism. B_0 in Table X represents the threshold value of brightness measured as a fraction of the standard high brightness. Brightness B, is proportional to illumination, I, and inasmuch as it is a brightness that is perceived the symbol B is used.

35. *Hue Sensibility.* — Notwithstanding the fact that the visible spectrum is generally considered to exhibit only six or seven colors, four of which, red, yellow, green, and blue are strikingly distinctive, there are theoretically present an infinite number of hues. The number of distinct hues that a person is able to distinguish depends upon the manner in which the experiment is conducted. Edridge-Green[4] states that he has 'never met with a man who could see more than 29 monochromatic patches in the spectrum.' Rayleigh,[5] who is able to detect the difference in hue of the sodium D lines (0.5890μ and 0.5896μ), could distinguish only 17 hues on Green's apparatus, and claims this is due to the method of comparing the patches. In Green's apparatus the principle is that of two opaque screens held over a spectrum and slightly separated from each other. One is then moved until the hue at its edge appears different from that at the edge of the other. With an apparatus employing the principle of the Maxwell color box Rayleigh was able to distinguish many more hues. By the use of spectral apparatus as high as 128 distinctly different spectral hues have been seen. It is not difficult to obtain by the use of dyed media a series of 25 distinct spectral hues. Ridgeway,[6] by beginning with papers dyed to represent six spectral hues and adding various intermediate hues, obtained 36 distinct hues. The data on hue sensibility vary considerably, which perhaps is due to

variations in the refinement and nature of the experimental methods employed.

Some excellent data have been obtained by Steindler[7] on hue sensibility for twelve subjects. The positions of the maxima differed somewhat for the various

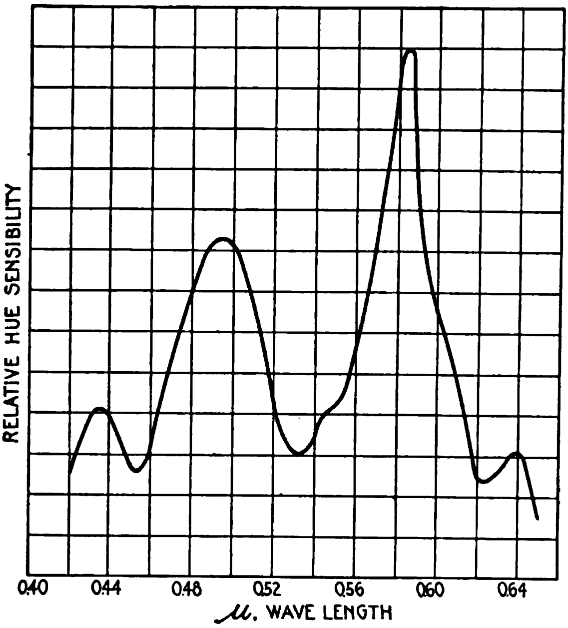

Fig. 66.—Hue sensibility. (Steindler's Eye.)

observers. The hue sensibility curve for Steindler's eye is shown in Fig. 66 and the mean positions of the maxima and minima of the hue sensibility curves for the twelve observers and the wave-length limen of 'just perceptible difference' are given in Table XI.

Nutting[8] has used the mean results obtained by Steindler in deriving a natural scale of color. These mean results, including Nutting's color scale, are plotted in Fig. 67. The hue sensibility curve, S, was plotted by connecting the mean positions of the minima and

TABLE XI

Steindler's Data on Hue Sensibility

(The mean for twelve eyes)

	Position	Perceptible limen
First maximum	0.455μ	0.0293μ
Second maximum	0.534	0.0334
Third maximum	0.621	0.0375
First minimum	0.440	0.0247
Second minimum	0.492	0.0136
Third minimum	0.581	0.0139
Fourth minimum	0.635	0.0300

maxima for the twelve observers with smooth curves. The limen (least perceptible difference in terms of μ) curve, L, is plotted in the same manner. For the

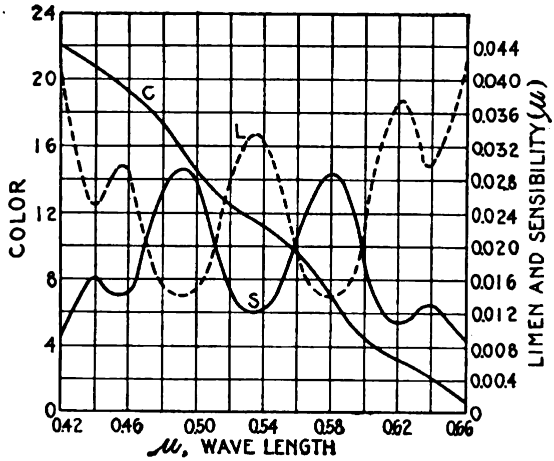

Fig. 67.—Hue sensibility, limen, and color scale.

details of the procedure adopted in obtaining the color curve, C, the reader is referred to the original paper. A difference of one unit in the color scale represents a difference in color that is just easily perceptible. It will be noted that the color curve

indicates there are 22 of these colors 'just easily perceptible' within the spectral limits shown.

36. *Saturation Sensibility.* — The data on the sensibility of the eye to changes in saturation are not very extensive or definite. Nutting [9] states that with his monochromatic colorimeter the probable error in the 'per cent white' observations on a nearly spectral matte orange pigment was about ten per cent. L. A. Jones [10] claims an accuracy of the order of three per cent for the 'per cent white' readings (Table VII) for this monochromatic colorimeter of improved type. The accuracy of course will vary with the hue, brightness, and degree of saturation of the colors. H. Aubert [11] determined the smallest sector of color that would be just apparent on a rotating white disk to be 2 or 3 degrees — less than one per cent. With black and gray disks he found that even smaller sectors were recognized. His experiments on the differential limen of color sensitivity indicated that on a black background the stimulus-increments for orange, blue, and red were respectively 0.95, 1.54, and 1.67 per cent in order to produce a just noticeable increase in saturation.

Geissler [12] studied the problem whether the number and sizes of the colored stimulus-increments corresponding to just noticeable saturation differences would lend themselves to a measure of saturation. The problem was attacked from two extremes; one by gradually reducing a maximally saturated pigment color, and the other by introducing more and more color into a colorless stimulus. He employed the rotating double color disk with the Zimmerman colored and gray papers illuminated with an artificial daylight devised by Ives and Luckiesh. In the first method he used red beginning with maximal sat-

uration — 360 degrees of red — for both the inner and outer concentric components of the double disk and gradually added small amounts of gray (of the same brightness as the red as measured with a flicker photometer) to the inner or smaller disk until it appeared just perceptibly less saturated than the outer or larger disk. This procedure was then reversed, the outer disk being decreased in saturation until the change was just perceptible as compared with the inner disk whose saturation was kept constant. This was done for seven different degrees of saturation, ranging from 360° of red to 110° of red *plus* 250° of gray of the same brightness as measured by the flicker photometer. His results indicate that the stimulus-increments corresponding to just noticeable saturation-differences are approximately constant (about 4° of gray) at such different stages of saturation as 325° red *plus* 35° gray, 230° red *plus* 130° gray, and 110° red *plus* 250° gray. Geissler states that 'it seems fair to assume that the increment-values would have remained constant at the intervening stages and perhaps also at a stage not far removed from the absolute color-limen,' which latter averaged for the four observers with the red paper about 1.2°. That is, a sector of 1.2° of red when mixed with 358.8° gray causes a just perceptible appearance of color. It appears from the foregoing that the estimated number of least perceptible differences in saturation of the red pigment under the conditions of the experiment is about 100.

Another group of experiments was made with nine observers using red, yellow, green, and blue colored papers and their corresponding grays. These measurements were made for each eye separately and for binocular vision. Geissler places no great

emphasis upon the absolute values of the results because of the lack of sufficient observers and the incompleteness of the investigation at present. However, it is of interest to give the mean results for the nine observers. The averages for binocular vision were, as a rule, lower than for monocular vision. The results for all observers for monocular and binocular vision gave as the mean limenal values of color saturation for red, yellow, green, and blue respectively, 2.23°, 5.81°, 7.19°, and 2.99°. That is, these values represent the smallest increments required to distinguish between 'color and no color.' The comparison was made between a gray disk and a concentric disk of the same gray in which the color was introduced. The brightnesses were previously equated by means of a flicker photometer. The colored papers differed from each other in brightness and saturation, which appeared to have an influence on the values of just perceptible saturation-difference. Since the green requires a limen three times as great as that of red it appears to Geissler that it is reasonable to assume that its saturation is only one-third as great as the red and about one-half that of the blue. These figures agree approximately with a number of estimates of saturations made by some of the observers, but in the absence of sufficient data little emphasis is given to this point. Experiments with a practically color-blind subject indicated that his limenal values were extremely high, being 37°, 18°, 140°, and 8.25° respectively for the red, yellow, green, and blue papers. No analysis of his defect was made.

There appears to be a need for a further exploration in this interesting field.

37. *Visual Acuity in Lights of Different Colors.* —

As has already been shown the eye is not achromatic; that is, rays differing in wave-length do not come to a focus at the same point, with the result that the image of an object illuminated by light of extended spectral character is not sharply defined upon the retina. Louis Bell [13] compared the acuity of the eye or its ability to distinguish fine detail in tungsten and mercury arc lights and obtained results indicating an advantage for the latter illuminant. This he attributed to the more nearly monochromatic light emitted by the mercury arc. It will be remembered (Fig. 4) that the preponderance of visible rays is confined to a rather narrow wave-length range in the yellow and green regions of the mercury spectrum. The author [14] verified these results and extended the investigation to lights of the same color but differing in spectral character. By using the lights whose spectra are shown in Fig. 17, no difficulties of color photometry were encountered. Screens *b*, *c*, *d*, used with a vacuum tungsten lamp operating at 7.9 lumens per watt yielded lights of the same yellow color but of different spectral character. Likewise screens *e* and *f* yielded two green lights, one purely monochromatic (mercury green line), and the other a green of extended spectral character. The data, except in case 4, Table XII, were not obtained as usual by using fine detail at the limit of discrimination but instead, in terms of equal 'readability' of a page of type, which proved after some practise to be a rather definite criterion. Some such method should be applicable to many practical investigations in lighting, for it renders results in terms of a criterion which, although apparently indefinite, is found to be quite definite and one which renders results full of significance. The results for the

TABLE XII

Relative Illumination for Equal Readability

Case	Source	Screen	Color	Approx. foot candles	Relative illumination
1	Mercury arc Tungsten lamp	f e	green line green	2.0	1.00 1.75
2	Tungsten lamp Tungsten lamp	d c	yellow yellow	4.0	1.00 1.33
3	Sodium lines Tungsten lamp	none c	yellow lines yellow	0.5	1.00 1.66
4	Mercury arc Tungsten lamp	f e	green line green	0.6	1.00 5.10

author's eye are shown in Table XII and are given in terms of the relative illumination required for equal readability of a page of type. In case 4 an acuity object proposed by H. E. Ives [15] and developed by P. W. Cobb was used. Here the criterion was the ability to perceive fine lines at the limit of discrimination.

Other observers obtained results of a similar nature with the same apparatus. No stress is laid upon the accuracy of the absolute values, but it is conclusively evident that monochromatic light is superior for discriminating fine detail. Later it was shown, [16] as was expected from the foregoing, that monochromatic light was superior to daylight for discriminating fine detail. In this case the Ives acuity object was viewed against a white magnesium oxide surface which was illuminated to an intensity of 10 meter candles (approximately one foot candle). The visual acuity on the Snellen scale was found to be 1.28 and 1.11 respectively for daylight, and mono-

chromatic green light of equal intensities and results for tungsten light and daylight were practically identical. Another experiment showed that for visual acuity of 1.28 on the Snellen scale the intensity of illumination with daylight or tungsten light was nearly three times that required for the same visual acuity with monochromatic green light. As the brightness of the background was increased it appeared that the difference in visual acuity under a given illumination of tungsten light and monochromatic light decreased.

The superior defining power of monochromatic light having been demonstrated, it is of interest to learn if there is any difference in the defining power of monochromatic lights of different colors. Dow [17] measured visual acuity in light of different colors using electric lamps screened with colored media and arrived at the conclusion that the blue-green region of the spectrum showed greater defining power. Ashe [18] used red, green, blue and clear glasses with incandescent lamps and found visual acuity least for the red and increasing in the order green, blue and clear glass for the same illumination; however, the data were too incomplete to warrant any definite conclusions. Löeser [19] used red, green, and white papers on which black characters were printed. The papers were brought to equal brightness and visual acuity was determined by noting the greatest distance at which the observer could distinguish the details on the papers. He found acuity greater for green light than for red light, and also that the characters on the white card could be distinguished at nearly as great a distance as those on the green card. A serious defect in this method is the fact that, the distances not being constant, the

change required in the accommodation of the eye complicates the results. Uhthoff [20] determined visual acuity in monochromatic lights of different wave-lengths, but gives no data on the relative brightnesses of the colored lights. A serious defect in most of the above work is the fact that the lights were neither monochromatic nor did their spectra extend over equal ranges of wave-lengths. The same criticism is applicable to the work of Rice,[21] who performed an extensive investigation of the problem.

In order to determine visual acuity in monochromatic lights of different colors at ordinary bright-

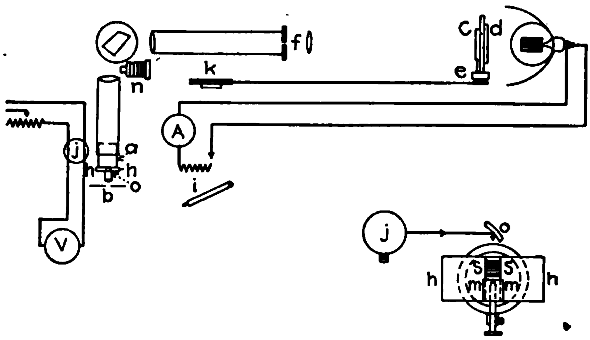

Fig. 68.—Apparatus for determining visual acuity in monochromatic lights.

nesses, the author [22] devised the apparatus shown diagrammatically in Fig. 68. The lines of the acuity object,[15] *c*, having a highly illuminated ground glass background, *d*, were focused crosswise on the slit of a Hilger wave-length spectrometer by the lens, *f*. On looking into the eyepiece these lines were viewed against a background whose color depended upon the position of the prism, the wave-length being indicated on the drum, *n*. On the pointer in the eyepiece was mounted a minute piece of magnesium sulphate, *mm*, at an angle leaning away from the eye at the top. This was illuminated by means of the frosted tung-

sten lamp, *j*, the light being reflected downward by the mirror, *o*. Slides *hh* controlled the width of the photometric field, and an artificial pupil, *b*, was placed in front of the eyepiece. The drum, *k*, controlled by means of a belt the size of the lines of the test object which was read from drum *e*. The photometric balance was made, in the case of each monochromatic light used, by balancing it against the white surface *mm*, the lines of the acuity object at the time being too small to be visible. A feature of this acuity object which is essential for such a use is that the average brightness of the object is constant regardless of the width of the lines. Of course in making the photometric balance the uncertainties of color photometry are present, but these are not of much importance in this investigation, because visual acuity changes very slowly with change in brightness of the object at the illumination used; therefore, a large error in the photometric measurements would cause but a slight error in the visual acuity measurements. The brightness of the photometric field as seen by the eye through the artificial pupil was equivalent to the brightness of a white surface illuminated to an intensity of 4.2 foot candles. After the photometric balance was made by varying the current through the large lamp illuminating the test object, the lamp, *j*, was extinguished and a series of acuity settings were made by varying the size of the lines. The results obtained are shown in Fig. 69. Curves *a*, *c*, represent extreme series made by the author showing the fluctuation in the ability of the eye to distinguish fine details, and *b* is the mean curve of a great many observations. Curves *d* and *e* represent single series of observations (ten readings at each point) made by two other observers.

In every case the observer was permitted to focus the instrument. These data indicate an advantage in the defining power of monochromatic yellow light over other monochromatic lights of equal brightness. In order to extend the observations into the violet end of the spectrum, the test object was illuminated by means of a mercury arc. The mean results for each of two observers are shown in Fig. 70, for three mercury lines. Curve *F* was combined with curve *b* in Fig. 69 (obtained by the same observer) which

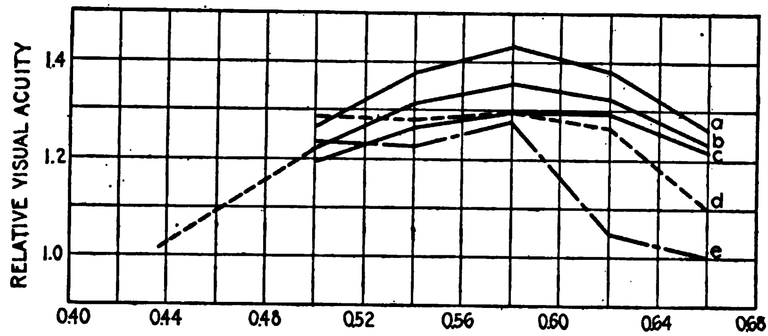

Fig. 69.—Visual acuity in monochromatic lights of equal brightness.

extended the latter as indicated. This investigation indicates that monochromatic lights differ in their defining power and that yellow monochromatic light is superior to others in this respect. It was also found that for a given change in brightness of the test object the change in visual acuity was least for yellow monochromatic light than for light of any other spectral hue.

A striking experiment illustrating the effect of spectral character of light on visual acuity is given below. The test-object was viewed through an ethyl violet screen (purple under the illumination from a tungsten lamp) and visual acuity settings were made. After obtaining the mean of a series of observations

a yellow screen was also placed before the eye. This screen absorbed the blue and violet rays transmitted by the purple screen, thus reducing the illumination at least 50 per cent. Notwithstanding this reduction in illumination visual acuity noticeably *increased.* In place of the yellow screen was now substituted a blue screen which absorbed the red rays transmitted

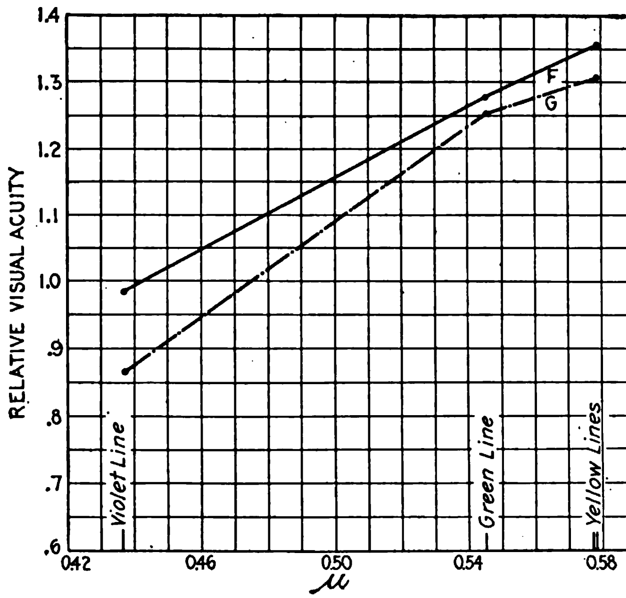

Fig. 70.—Visual acuity in the mercury spectrum, the lines being reduced to equal brightness.

by the purple screen, the resulting light being blue. Again visual acuity increased, notwithstanding the reduction in brightness. This experiment strikingly demonstrates the influences of chromatic aberration and spectral character of light on the ability to distinguish fine detail.

It is interesting to note some results on the legibility of colored advertisements. Le Courrier du Livre [23] reported the legibility of various combinations

for reading at a considerable distance, the most legible print being black on a yellow background. The order of merit was found to be as follows:

1. Black on yellow
2. Green on white
3. Red on white
4. Blue on white
5. White on blue
6. Black on white
7. Yellow on black
8. White on red
9. White on green
10. White on black
11. Red on yellow
12. Green on red
13. Red on green

It is noteworthy that in this list the customary black-on-white combination is sixth on the list. These results are interesting, although perhaps not final, owing to the many variables that enter such a problem.

38. *Growth and Decay of Color Sensations.* — Many investigators have studied the problem of the effect of time of exposure and intensity of the stimulus on the growth and decay of luminous sensations. It has been noted (# 14) that colors are seen on rotating, at a proper speed, a disk composed of black and white sectors. It appears that this is due, in part at least, to the difference in the rate of growth and decay of the various color sensations excited by white light. Of the work in this field, that of Broca and Sulzer[24] is especially comprehensive. They compare the brightness of a white screen illuminated by a light of short duration with that due to a standard steady light. Some of their results which are plotted in Fig. 71 show that, excepting for lights of low intensity, the luminous sensation 'overshoots' its final value; that is, the maximum luminous sensation is passed a comparatively short time after the beginning of the exposure and that the luminous sensation reaches a steady value less than the maximum

only after the elapse of an appreciable fraction of a second (depending more or less upon the intensity). The numbers on the curves indicate the final steady value of the various stimuli. Their data obtained with colored light, plotted in Fig. 72, indicates that under the stimulation of blue rays the luminous

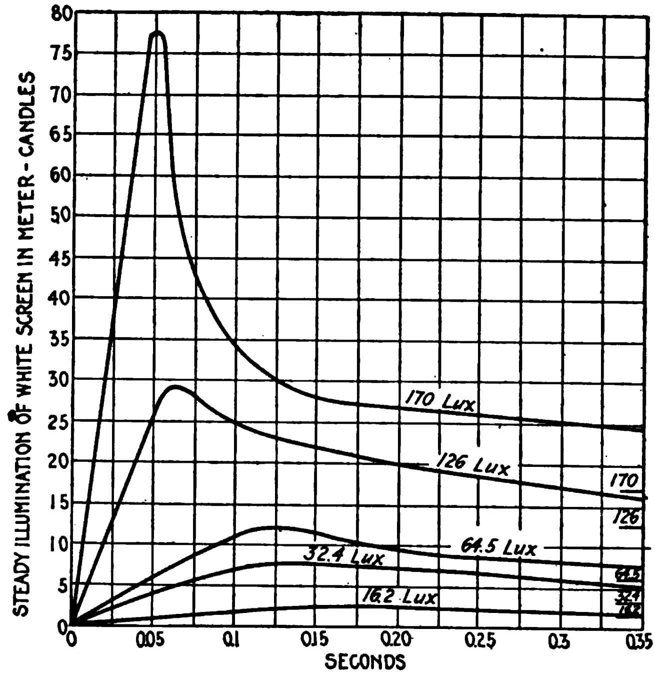

Fig. 71.—The growth and decay curves for white light sensation. (Broca and Sulzer.)

sensation overshoots very much more than in the case of red or green light, the latter showing the least overshooting.

In studying the growth and decay of color sensations in connection with the flicker photometer [25] some data of interest here were obtained. Red and blue-green lights, practically complementary, were matched by the ordinary direct comparison method of photom-

etry. These were then separately flickered against darkness by means of a rotating disk with equal open and closed sectors. The maximum brightness of the flickering light was compared with a steady brightness of the same color for a large range of flicker frequencies. The data is shown in Fig. 73,

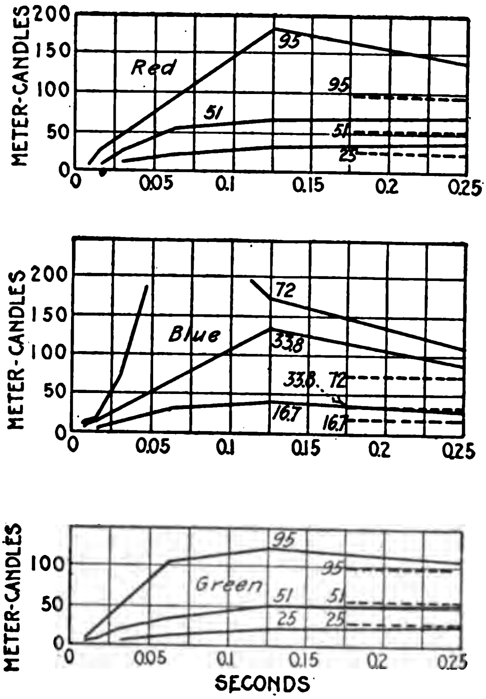

Fig. 72.—The growth and decay curves of color sensations.

the initials *R* and *G* representing the red and blue-green lights and the subscripts, high and lower intensities. The intensities used were those ordinarily considered satisfactory in photometry as is indicated by the frequency in cycles per second required to cause flicker to disappear. It will be noted that the colored lights were alternated against darkness, the steady values of the colored lights (sectors open) as

determined by the direct comparison method being represented by unity on the relative brightness scale. The flicker of G_L, R_L, G_H, and R_H completely disappeared at frequencies corresponding respectively to A, B, C, and D.

Next red and blue-green brightnesses equivalent to the foregoing were placed so that on one side of

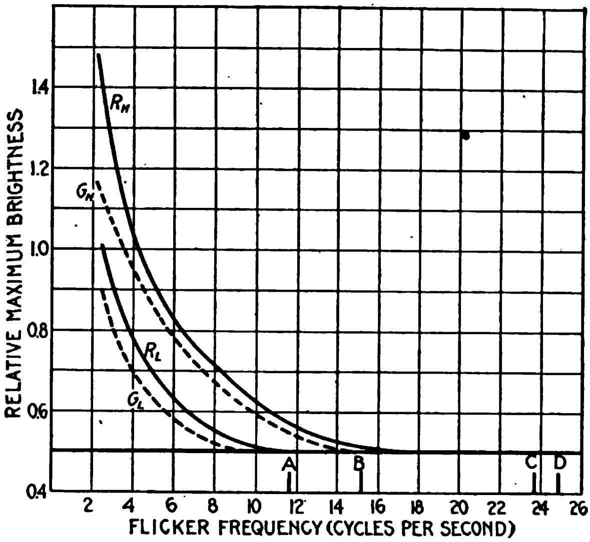

Fig. 73.—Showing the maxima attained by flickering lights at various frequencies.

the photometer field a red light flickered on a steady blue-green field and vice versa on the other side. This was done by means of identical sectored disks (180° opening) placed one on each side of the photometer. On one side a disk intercepted the blue-green light and on the other the red light was intercepted. On increasing the speed of rotation of the disks (which were fastened to the same shaft) the side on which blue-green light flickered upon a steady red field became quiescent long before the flicker

disappeared on the other side. At all times when flicker was visible the side upon which red flickered on a steady blue-green field appeared to attain higher maximum values of brightness and to be more agitated. The brightnesses on either side were later

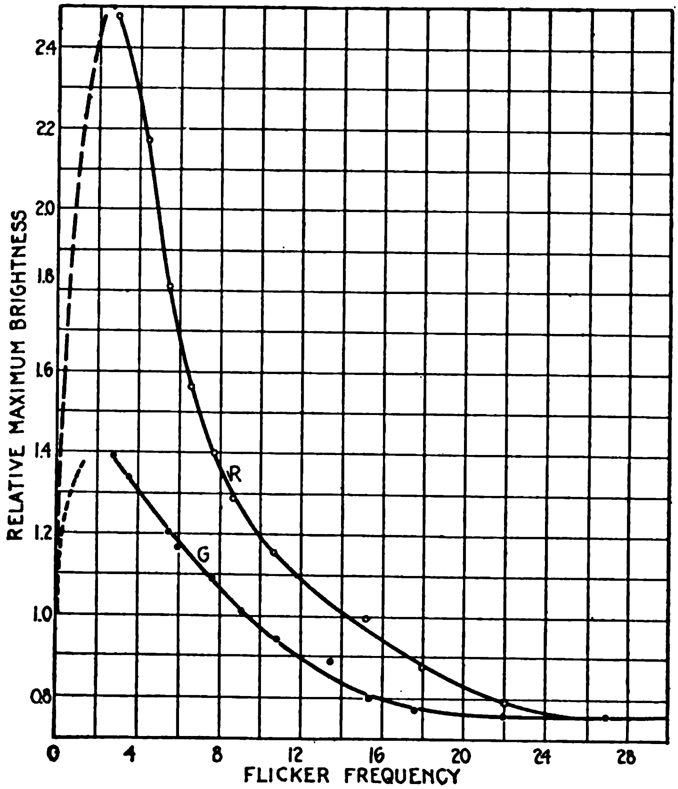

Fig. 74.—Showing the maxima of sensations produced by flickering red light on a steady green field (R), and vice versa (G).

measured separately against a steady white light (there being little color difference excepting at low speeds) throughout a wide range of frequencies. These results are shown in Fig. 74, *R* and *G* indicating that red and blue-green were respectively the flickering components. The steady value reached at

a high frequency is 0.75, unity being taken as the steady value at zero speed with the sectors open. The latter intercept only one of the two components which make up the brightness on either side; therefore, the sectors being of 50% transmission, the final value at a high frequency of alternation is 0.75 of the original steady value with sectors open. Of course these experiments involve the measurement of the brightness of surfaces differing in color, but it is this problem that was involved in the study. All steady brightnesses were chosen equal as measured by an ordinary direct-comparison photometer. While these effects of different rates of growth and decay of color sensations are operative when there is an apparent flicker, evidence points to the disappearance of such influence upon the brightness of a mixture of colored light by alternately presenting the colored stimuli when the rate of alternation is so high that flicker has disappeared. For instance the foregoing red and blue-green lights were mixed by alternating them by means of a sectored disk (50% opening) and also by directly superposing the steady lights. The former mixture was found to be just one-half as bright as the latter, within the slight possible errors of the experiment. There was no color difference present in this experiment so the photometric data is correct to within one per cent. Other evidence of the same kind was obtained by comparing two yellow lights of the same hue, but differing in spectral character, by means of both the flicker and direct comparison methods of photometry. Identical results were obtained by the two methods. These results were also confirmed by comparing tungsten light by the two methods with a light of the same hue consisting of red and blue-green lights. (See # 55.)

Talbot [26] long ago expounded the law that a sectored disk rotating at high speed transmitted light in direct proportion to the angular openings of the sectors. This law has been stated by Helmholtz [27] as follows: 'If any part of the retina is excited with intermittent light, recurring periodically and regularly in the same way, and if the period is sufficiently short, a continuous impression will result which is the same as that which would result if the total light received during each period were uniformly distributed throughout the whole period." Plateau,[28] Kleiner,[29] Weideman and Messerschmidt,[30] Ferry,[31] Lummer and Brodhun,[32] Aubert,[33] Hyde,[34] and others have investigated the problem, and have generally agreed that the law holds for white light. Fick concluded that it holds only at moderate intensities and Ferry verified the law for white light but found discrepancies when one side of the photometer field was bluish as compared to the other side. Hyde, after a thorough investigation of the problem, concluded that the law holds within the accuracy of the work (about 0.3%) for the range of sectors used by him, namely from 288° to 10° in opening. He further concluded that the law held for red, green, and blue lights within the accuracy of precision photometric apparatus, and found that when a color difference existed on the two sides of the photometer field no appreciable deviation from the law was observed. The author has had many opportunities to test the law for colored lights and found no deviations within the accuracy of the experimental work, which was usually well within one per cent. The sectored disk, therefore, affords a means of altering the intensity of colored light in definitely measurable amounts.

Lights of very short duration are perceptible if

intense enough. For instance, a lightning flash as short as one-millionth of a second is visible and by rotating mirrors flashes of light as short as one eight-millionth of a second have been perceived. Blondel and Rey [35] studied the perception of lights of short duration at their range limits. Bloch [36] had previously contended that the excitation necessary for the production of the minimum sensation was perceptibly constant and proportional to the product of the brightness and the duration. Charpentier [37] verified the law within certain limits. Blondel and Rey conclude that Bloch's law can be applied only to intense lights of very short duration. After a very extended investigation they deduce a simple law, $(B - B_0)\, t = a B_0$, where B_0 is the minimum perceptible brightness of the field, t the duration of the stimulus in seconds, and a is a constant of time equal to 0.21 second. They show by simple integration one can deduce from the law of the flashes which are not uniform, their range and the intensity of the equivalent constant light from the point of view of range,

$$\frac{\int_{t_1}^{t_2} I_h\, dt}{a + t_2 - t_1}$$

where I_h represents the photometric intensities of the luminous points measured in a horizontal section of the beam and referred to unit distance. They conclude by taking into consideration the curves of sensation of Broca and Sulzer [24] 'that the maximum utilization of a source of light must demand short flashes without its being necessary to take any notice of an inferior limit of the period of the signals, except in the case of telegraphic signals. It more-

over suffices that the period of the flash, $t_2 - t_1$, should become a negligible quantity in the presence of the constant a, in order that a maximum efficiency may be assured.'

On alternating a given brightness with darkness by means of a sectored disk with 50% openings, a violent flicker is evident at low speeds; however, there is a certain minimum frequency, called the critical frequency, at which the flicker just disappears. The critical frequency depends upon the intensity of illumination or brightness of the observed field and increases with the brightness. Porter[33] has found

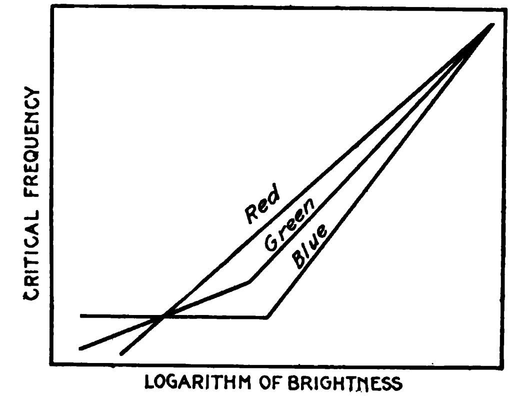

Fig. 75.—Showing the relation between brightness and critical frequency for colored stimuli.

that the relationship, $f = a \log I + b$, holds for white light where f is the critical frequency, I, the illumination, and a and b are constants; that is, there is a straight line relation between the critical frequency and the logarithm of illumination. The constant, a, has two values, one for brightnesses above those resulting from illuminations on a white surface greater than about 0.25 meter candles and one below. It is thought by adherents to the von Kries 'duplicity

theory' (#48) that this point of abrupt change in slope corresponds to the change from cone to rod vision. Haycraft[39] has studied the critical frequency for spectral lights, but the results are complicated, because the intensity of the various rays was not constant throughout the spectrum. Ives[40] studied the relation between critical frequency and brightness for various spectral rays and obtained results which he expresses diagrammatically as shown in Fig. 75, the logarithm of brightness being plotted against critical frequency. It is noted that the 'red' curve shows no change in direction at low intensities. The blue curve changes from a diagonal to a horizontal straight line; that is, at low illuminations the critical frequency becomes constant for blue light of various feeble intensities. Intermediate curves represent spectral colors between red and blue. It is significant to note that the slopes of the curves are different for the higher illuminations, the 'blue' slope being steeper than the 'red' slope, which indicates that the Purkinje phenomenon is operative.

The author [25] has shown that the critical frequency depends upon the wave form of the stimulus or the contour of flicker. Some of the data for white light is shown in Fig. 76. In cases *a*, *b*, *c*, the maximum, minimum, and mean cyclic illumination were respectively the same. A difference in critical frequency was obtained throughout a wide range of illumination, the critical frequency being higher the greater the period of darkness in a given cycle. This also appeared to hold for colored lights, but no extensive study has yet been made.

39. *Signaling.* — The chief requisite of a colored light for signaling purposes is high intensity, because its range depends largely upon this factor. This

precludes the use of very pure colors owing to low intensities obtainable in practise, and for this reason signal glasses are a compromise between saturation of color and transparency. As is seen by the redness of the setting sun, red rays are less absorbed by smoke and dust in the atmosphere than the blue rays, therefore, a red signal should have a greater range than a blue signal through a smoke and dust laden

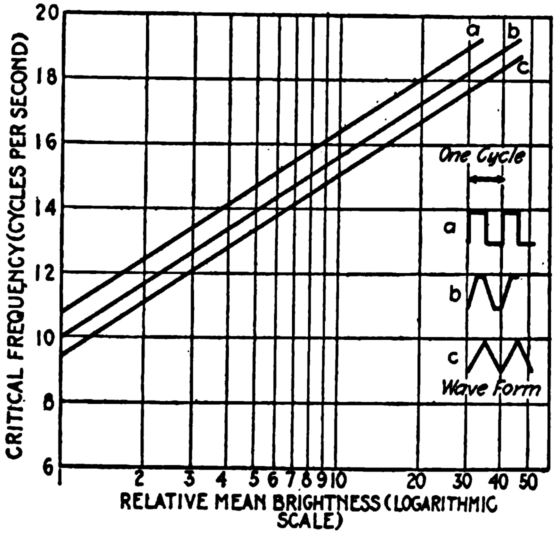

Fig. 76.—Effect of contour of flicker on critical or vanishing-flicker frequency.

atmosphere. Churchill[41] quotes results obtained by the Geheimrat Koerter of the German Lighthouse Board on the selective absorption of artificial fog. The results indicated that red rays were absorbed to a greater degree (about 20% more) than blue rays. These results indicate that the selective absorption of clouds plays no part in the shifting of the color of the setting sun toward red. On the other hand the German Government in about 1900 found that an installation of arc lamps in a lighthouse on the island of

Heligoland had a lesser range in a fog than a kerosene light of only one-hundredth the candle-power. The former contains a predominance of blue rays in comparison with the latter, which from the foregoing tests in artificial fog apparently suffered less absorption.

The German Lighthouse Board of Hamburg in 1894 carried out an extensive series of tests on the range of signal lights with the following results as presented by Churchill, where *R* represents the range in miles and *I* the candle-power.

For white light in clear weather $R = 1.53\sqrt{I}$

For white light in rainy weather $R = 1.09\sqrt{I}$

For green light in clear weather $R = 1.6\sqrt[3]{I}$

M. Busstyn [42] estimates the range of red light as $R = 1.5\sqrt{I}$. The spectral character of the illuminant of course has an important influence on the color of the signal glass.

It is interesting to note that on a certain modern battleship a lighting system of blue lamps has been installed for use at night when in action. The reason given for installing blue lights is that they are invisible to the enemy. No information was obtainable as to whether the short range is due to the faintness of the blue lights or to a supposed lower range for blue than for yellow light of equal intensity.

The Railway Signal Association (1908) after extensive tests arrived at the conclusions expressed in Table XIII for the effective range of the principal signal colors under average weather conditions. The colored glasses are assumed to be used with the customary semaphore lamp and lens.

Paterson and Dudding [43] have performed some interesting experiments on the visibility of point

TABLE XIII

Color	Effective range (miles)	Approx. transmission coef. of glass in service
Red	3 to 3.5	0.20
Yellow	1 to 1.5	.35
Green	2.5 to 3.0	.17
Blue	0.5 to 0.75	.03
Purple	0.5 to 0.75	.03
Lunar-white	2 to 2.5	.15

sources made by placing plates containing minute apertures before a wax flame. While most of their work was done indoors at distances as great as 550 feet, an experiment on the visibility of the light from tungsten and carbon incandescent lamps over ranges which extended more than a mile showed no difference in the carrying power of these lights on a clear night. They established the theorem that the visibility of a point source is proportional to the candle-power of the source and to the inverse square of the distance. They also found that the visibility is independent of the intrinsic brightness for sources subtending less than two minutes of arc. In this connection it might be noted that they assumed a point source to be one whose linear dimensions subtend an angle at the eye less than the resolving power of the eye, i.e. about 30 seconds of arc for a mean wave-length of 0.5μ and pupillary aperture of 4.5 mm. They found that the visibilities of red and green lights in clear air were closely proportional to the inverse square of the distance. On slightly illuminating the field surrounding the point source there was a loss in visibility of about 10% for a red light, 15% for a white light, and 18% for a green light, all being of equal candle-power. Their method

of determining the candle-power of the red and green lights in the latter experiment was to determine the visibility of the unknown in terms of the visibility of a white light of known candle-power assuming the visibility porportional to the candle-power and the inverse square of the distance. Their unit of visibility was equivalent to the visibility of a point source of one candle-power at 1000 meters distance, and they state that the lowest visibility considered desirable was 0.12 of this unit. Their results for white light agree fairly well with those obtained by the Deutsche Seewarte of 1894, as is shown in Table XIV.

TABLE XIV

Range	(Deutsche Seewarte) Candle power required in clear weather	(Paterson & Dudding) Computed from results of experiment
1 sea-mile (1855 meters)	0.47	0.41
2 sea-miles (3710 meters)	1.9	1.6
5 sea-miles (9275 meters)	11.8	10.0

By using artificial pupils they found little evidence of any influence of the spherical aberration of the eye on the visibility of point sources. They showed by using positive lenses that a green light equivalent to a point source was greatly dimmed relatively to a red light of similar dimension, which they attribute to the chromatic aberration of the eye. They conclude that unless an observer has sufficient accommodation available to focus properly a green light at infinity the latter will appear dimmed in proportion to the amount this image is out of focus. This is not so likely to occur with red light, because images of this color do not require as much accommodation

in order to focus them on the retina. A purple roundel at some distance sometimes appears red in the center with blue diverging from it, which is attributed to chromatic aberration of the signal lens.

It is hardly necessary to state the importance of tests for color-blindness of eyes engaged in discriminating colored signals. Numerous test methods have been devised, but one that has been used very much is the Holmgren test, conducted with colored skeins of wool.

In the choice of signal colors the four most distinctive are red, yellow, green, and blue. To these can be added white (clear) and purple. The blue and purple owing to their low intensity are suitable only for short-range signals. Results by Churchill on the reaction times, or the intervals required to distinguish and name signals of different colors, were in general in the following order. Red was recognized and named in the shortest time, green ranked next, then yellow, and lastly white, which required the longest interval for recognition. The relative length of the time interval varied with different subjects, but the order given was found to be generally the case. Of course the spectral character of the illuminant has an important influence on the color of the signal glass.

40. *Other Uses for Colored Glasses.* — It is well known that dust and smoke (and very likely fog) scatter the visible rays of short wave-length more than those of longer wave-length. For this reason it is contended by some that, if the blue and violet rays are subtracted from white light, the remaining light (yellow in color) will enable an observer to see further than the total light. It is of interest to inquire further into the matter. In the case of the search-

light, if the operator wishes to see a distant object in a fog he is required to look through an illuminated veil caused by scattered light, which results in decreasing the ability to distinguish the object. If it is true that the blue and violet rays are scattered more by the fog particles, the luminous veil would become more annoying for lights containing relatively greater amounts of blue rays. Rough quantitative tests by the author, employing auto lamps with parabolic reflectors, indicated that with yellow light, which was less intense than the total light by the amount of light absorbed by the yellow screen, objects in a fog could be seen more clearly than with the total light. There is another view-point, namely that of the person who desires to distinguish a light signal at a considerable distance. Here again an illuminated veil relatively near the light source if visible is likely to decrease the visibility of the signal light. This point, however, requires investigation.

Based on the foregoing principle many patents have been obtained for methods of eliminating the violet rays. Colored glasses, gold-plated reflectors, fluorescent glass reflectors, etc., have been employed, but all for the same object. A noteworthy problem of projection arises with the carbon arc search-light. In order to obtain a beam of parallel light by means of silvered reflectors the area that emits light must be small and be located at the focus of a parabolic reflector. With high-amperage arcs an appreciable portion of the light is emitted by the arc flame of relatively large area as compared with the crater of the positive carbon which is located at the focus of the parabolic reflector. The light from the arc flame has a decided violet tinge as compared with the light from the crater, and furthermore, being out of the focus

of the parabolic reflector, its light is not 'paralleled,' but escapes in a cone of relatively large angle. By using a yellowish glass in the aperture of the searchlight, this light of a bluish tinge is greatly reduced in comparison with the reduction of the yellower light from the crater, thus decreasing the possible annoyance due to the 'luminous veil.' The same result would be obtained if the 'look-out' wore yellow glasses. In the case of a very powerful searchlight such a glass in the aperture probably would be broken by the rise in temperature due to its absorption of radiant energy. If it were inconvenient for the look-outs to wear the yellow glasses before their eyes there would be some virtue in the gold-plated reflector which would reduce the amount of blue and violet light in the reflected light. However, in all such cases there is a cone of light which escapes directly without being altered by selective reflection. In the application of the foregoing principle to auto headlights or to any projectors employing electric incandescent lamps, any possible objectionable effect of the excessive scattering of violet and blue rays can be overcome by incorporating the yellow glass directly in the lamp bulb, by applying a yellow coloring to the exterior of the bulb, by inserting a yellow glass in the aperture of the reflector, or by wearing yellowish glasses before the eyes. An interesting case is found in a fluorescent glass reflector (silvered on the back surface) which absorbs most of the violet and blue rays. One of the claims advanced for this reflector is that it utilizes the ultra-violet, violet, and blue rays of the incandescent lamp by taking advantage of the fluorescent property of uranium glass which converts these rays into yellow-green light; however, these rays constitute a very

small proportion of the total visible rays in the light from electric incandescent lamps ordinarily used for such purposes. Furthermore, the fluorescent yellow-green light produced by these rays is not 'directed' by the parabolic reflector, because this light is emitted in all directions. On looking at such a reflector it appears of a yellowish green tint, but close examination shows that the yellow-green fluorescent light is emitted by the glass in all directions. Therefore, no practical gain in intensity of the directed beam results from the conversion of the ultra-violet, violet, and blue rays into yellow-green light, because the latter is diffusely emitted and the effect of such a fluorescent glass amounts to little more than eliminating most of the violet and blue rays from the radiation that is intercepted by the reflector. In this case there is also a cone of unaltered light, equal in solid angle to that subtended by the aperture of the reflector, which escapes 'undirected.' This scheme appears to have little value, inasmuch as a yellow glass in the aperture of the reflector would accomplish the purpose in a more satisfactory and simple manner.

Amber, yellow, and greenish yellow glasses have been used successfully for eliminating glare from the blue sky. Riflemen have found such glasses of extreme value in range shooting and a number of sportsman's glasses are available in the market. In the case of amber or greenish yellow glasses the improved condition of seeing is perhaps largely due to the reduction of glare from the blue sky, but also in part to an increased defining power due to the elimination of blue and violet rays and a relative reduction of the extreme red rays (#37). An illustration of the effect of greenish-yellow glasses [44] in increasing the ease of distinguishing detail is shown

in Fig. 77. An acuity object [15] (#37) was set up in the shade of a building on a clear day and light reached the object from at least one-half of the open sky. No direct light from the sun reached the eye, test object, or immediate surroundings. The author who made the observations wore no visor to shield the eyes. Only a slight sensation of discomfort was apparent before beginning the test; however, as soon as acuity observations were begun the glare became very evident and rapidly grew painful. Five readings

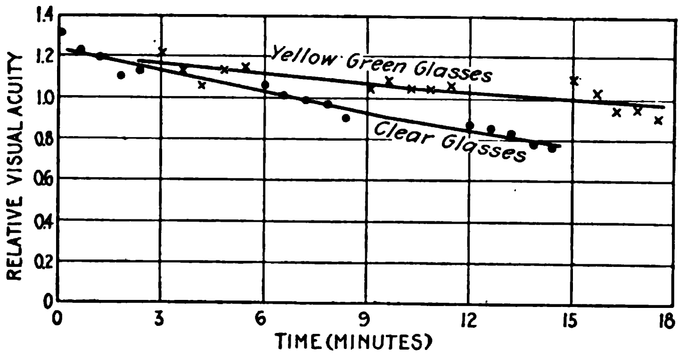

Fig. 77.—Effect of yellow-green glasses on vision under a bright sky.

were made first through clear correcting glasses (represented by the black dots) and as quickly as possible the clear glasses were replaced by yellow-green glasses of about 50 per cent transmission for the total light and five acuity readings were taken (represented by crosses). A decided decrease in discomfort was experienced when wearing the yellow-green glasses and, as will be noted, visual acuity is higher in this case, notwithstanding the decrease in illumination was fully 50 per cent. These glasses were again replaced by clear glasses and five acuity readings were made. This procedure was continued as indicated in Fig. 77. The interval of time required

to make five readings including the change of glasses was the same in each case (being three minutes), but the actual time of making the individual readings was not noted; therefore, they are plotted at equal intervals. While the above conditions are rather complex and involve problems worthy of much careful investigation, the experiment answered the intended purpose in bringing forth several points: (1) Glare conditions are not always apparent when the eyes are not engaged in serious work such as reading or distinguishing fine detail. However, bad lighting conditions are readily recognized when the eyes are called upon to do such work. (2) There is a rapid falling off of visual acuity when the conditions of glare are severe. (3) Such a harmless appearing light source as a wide expanse of sky can produce a very severe condition of glare. The intrinsic brightness is very low as compared with artificial sources, but the quantity of light is high and the image of the sky is spread over a large portion of the retina. Its annoyance can be decreased by the use of colored glasses, which absorb much of the blue light. (4) There was an apparent recuperation of the eye during the periods that the yellow-green glasses were worn. (5) Notwithstanding the effect of glare (when clear glasses were worn) in reducing visual acuity the values of the latter when the colored glasses were worn remained considerably higher. (6) This experiment emphasizes the necessity of prolonging acuity readings over a considerable period if acuity is to be a criterion of the satisfactoriness of illumination conditions. Some of the increase in visual acuity when the yellow-green glasses were being worn can be accounted for by the nearer approach to monochromatism of the light that passed

through them. However, conditions indicated that the advantage was due very largely to a reduction in the glare from the sky because the glasses absorbed much of the blue and violet light. Other interesting conclusions can be drawn, but the illustration has already fulfilled its object in bringing forth the fact that glare conditions are very complex and that cognizance of glare often depends upon the character of the activities in which the eyes are engaged.

Glasses for protecting the eyes from visible, ultra-violet, or invisible rays are coming into prominence. In considering only the visible rays, colored glasses may be combined after the principle of the subtractive method of mixing colors (#18, Fig. 20, Plate II). A superabundance of violet, blue, or green rays can be reduced by the use of red glass. That is, a colored glass will greatly reduce rays roughly complementary in color. Spectrophotometric analyses, affording data such as are shown in Fig. 12, are quite necessary for intelligently combining glasses for protecting the eyes. Spectrophotographic analysis is a convenient means of studying the transmission characteristics of glasses in the ultra-violet region and radiometric methods are applicable to the infrared region. Ordinary glass is sufficiently protective against moderate amounts of ultra-violet energy. In ordinary lens thicknesses it is transparent to about 0.360μ, from which point it begins to absorb ultra-violet rays, becoming practically opaque to rays of shorter wave-length than 0.300μ. Some green, yellow, orange, and red glasses are totally opaque to all ultra-violet rays, but this cannot be ascertained by a mere visual inspection. However, the ultra-violet transmission can be roughly determined by means of a quartz spectrograph and an iron arc or a quartz mercury arc.

On focusing the spectrum of the radiation emitted by the quartz arc on a fluorescent material such as uranium glass, the various ultra-violet lines will be seen owing to their production of fluorescence. On inserting a specimen of glass before the slit of the spectrograph the region of absorption will be readily perceived by the disappearance or decrease in brightness of various fluorescent lines. The transmission

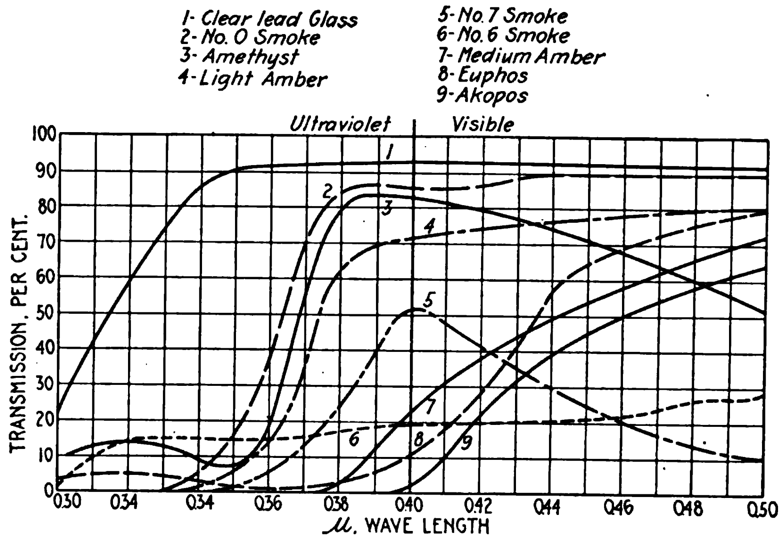

Fig. 78.—Ultra-violet transmission curves of various glasses.

of glasses in the ultra-violet region [45] has been determined by using a wide slit, the spectrum of the quartz mercury arc, and a combined photographic and photometric method. For qualitative analysis an iron arc is a satisfactory source rich in ultra-violet rays. Some specimen transmission curves for various optical glasses, employed for protecting the eyes from ultra-violet energy, are shown in Fig. 78, the ultra-violet region being represented to the left of the heavy vertical line at 0.40μ. It is interesting

to note the difference in ultra-violet absorption of the two samples of 'smoke' glass. Of course the absorption depends upon the thickness of the specimen and its density of color. All the glasses excepting three specimens, 3, 5, and 6, transmitted 50% or more of the total light from a tungsten lamp. Spectrophotographic analyses of various glasses are shown in Fig. 18.

In general it is no doubt advisable to use glasses as free from color as possible and yet providing protection if they are to be worn for long periods. Yellow-green glasses when otherwise filling the requirements appear to distort colors (more commonly encountered) less than medium amber. A striking instance was found in the lap-welding department of a steel mill, where the operators judge temperature visually. They became confused when wearing amber glasses, but found no difficulty in using yellow-green glasses. This brings to mind the fact that through a yellow-green glass transmitting only a limited region of the spectrum the relation of brightness and temperature appears practically the same as to the unobstructed eye when the luminous substance radiates light approximately the same as a black or 'gray' body. Years ago Crova suggested a method of photometry involving this principle (# 54). Schanz and Stockhausen, Vöege, Crookes, Parsons, and others have studied the subject of protecting the eye from harmful rays. Crookes [46] concludes with his associates that the relatively great amounts of infrared energy emitted by molten glass is responsible for glass-blowers' cataract, although this conclusion is questioned by some. He has made an exhaustive study of the manufacture of glasses for eye-protection and has published the valuable results.

Colored glasses are often used for bringing out certain colored portions of an object in more striking contrast with the surroundings. For instance, if a black-line drawing be made on blue-lined coördinate paper and viewed through a dense blue glass, the blue lines practically disappear. If the drawing be photographed through this glass the coördinate lines will not appear on the negative. In the same manner if blue and red appear upon the same background, one or the other can be made practically to disappear by using a colored screen of exactly the same color. Of course the degree of change in contrast will depend upon the purity of the colors and the care exercised in choosing the colored screen.

In using field glasses distant vision can be improved sometimes by the use of a light yellow screen which eliminates the blue haze from the visual image. In this connection it is well to note also that blue rays are normally out of focus at the retina. The author has experimented with colored screens for use with field glasses for detecting colored objects at a distance by altering their contrast with the surroundings by the use of colored screens. For instance, a khaki uniform (yellow-orange in color) can be made to appear either lighter or darker than the green foliage surrounding it by respectively using a yellow-orange screen or one of a complementary hue. For instance if the ratio of the brightness of a piece of khaki cloth to that of a certain green leaf be taken as unity under daylight illumination, through an ordinary orange filter this ratio became 1.5 and through a blue-green filter, 0.7. With care the contrast can be made practically a maximum. In the case of objects more striking in color the problem is not as difficult. Whether or not the reduction of

brightness more than offsets the advantage of increased contrast in distinguishing distant objects can be solved by actual trial. The point is mentioned here to illustrate the possibilities in the use of colored glasses as an aid to vision.

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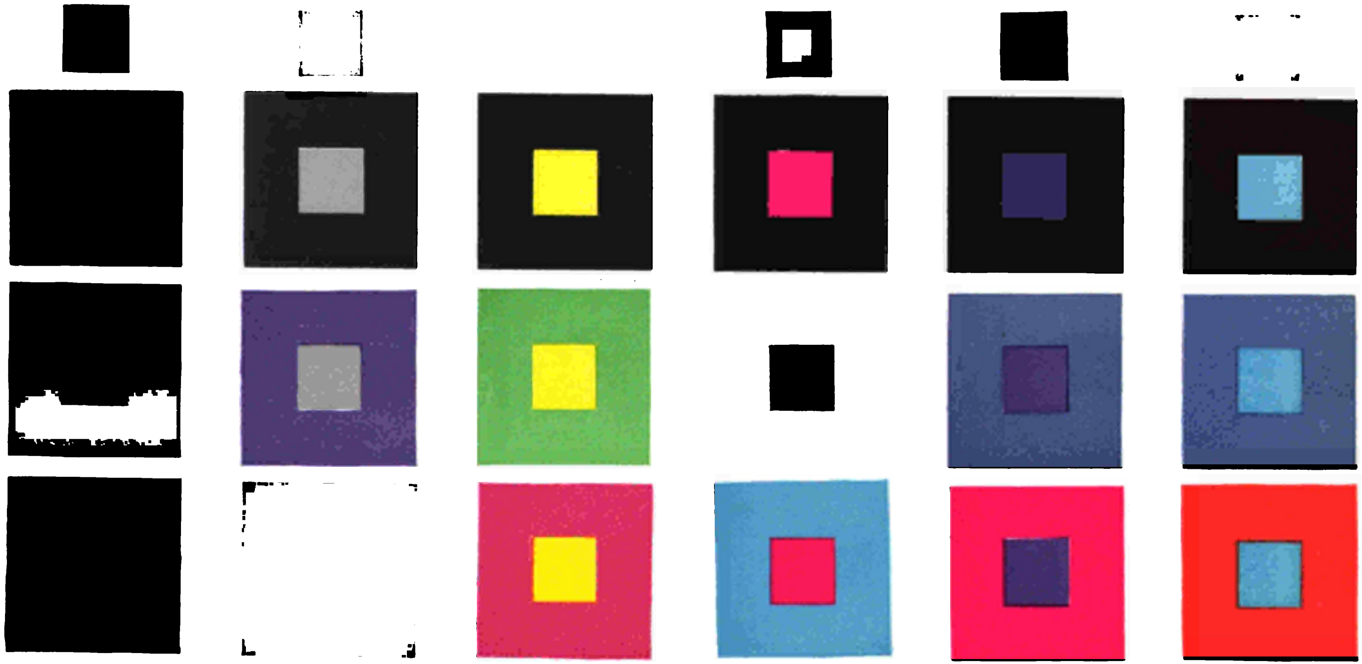

Plate III. Showing the effect of environment on the appearance of colors

CHAPT[illegible]

EFFECT OF ENVIRONMENT [illegible] OF CO[illegible]

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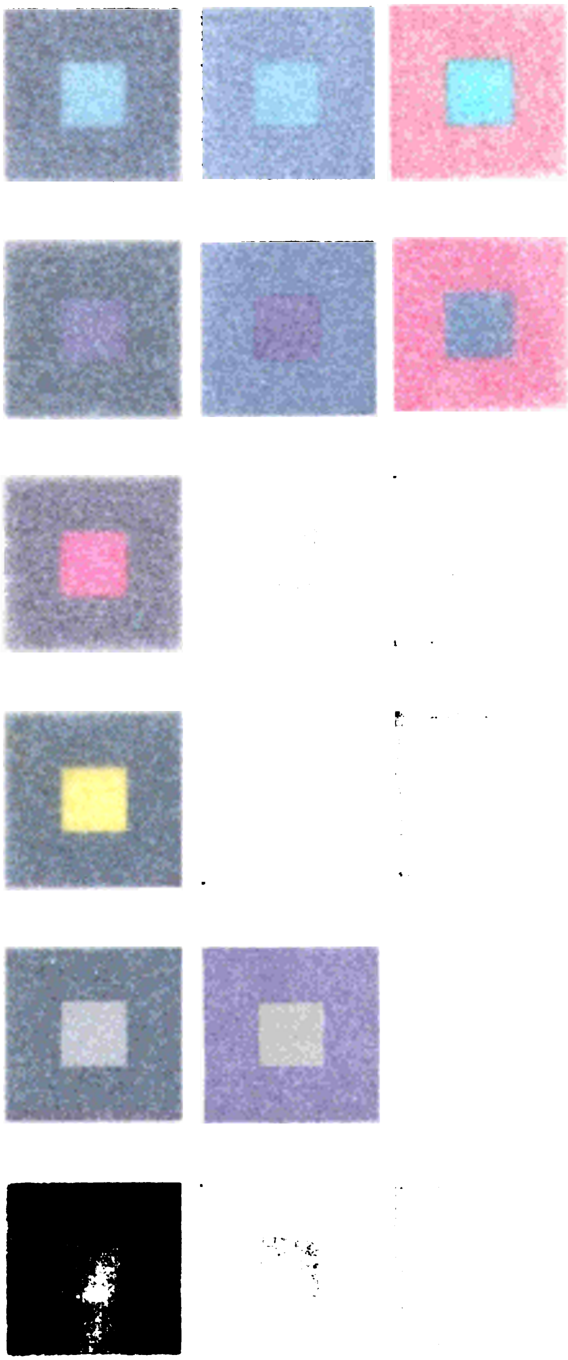
[illegible] of a colored image and [illegible]tion and [illegible] the retina affects its app[illegible] owing [illegible]ation of sensitivity of the v[illegible] tinal [illegible] MacDougal[1] found that with sm[illegible]ored areas (squares from 1 to 16 sq. cm. in area [illegible]ed from a distance of one meter) the larger are[illegible] appeared more saturated than the smaller. He fou[illegible] the saturating effect of increasing the area greatest for violet and decreasing in the order, blue, green, yellow, orange, red. He even concludes that a color [illegible]eld is not fully saturated until it extends over the



CHAPTER VII

EFFECT OF ENVIRONMENT ON THE APPEARANCE OF COLORS

41. Colors have been largely treated in other chapters as if they were invariable in appearance. However, the study and application of the science of color is rendered very complex owing to the fact that the appearance of a color is so modified by its *environment*. The intensity, spectral character, and distribution of the light illuminating it, the adaptation of the retina for light and color, the duration of the stimulus and the character of the stimulus preceding the one under consideration, the surroundings, the size and position of the retinal image, the surface character of the colored medium, all affect the appearance of a given color. Thus an analysis that holds for a color in a certain environment does not in general hold for the identical colored object viewed under other conditions.

The size of a colored image and its position and duration on the retina affects its appearance, owing to the variation of sensitivity of the various retinal zones. MacDougal[1] found that with small colored areas (squares from 1 to 16 sq. cm. in area viewed from a distance of one meter) the larger areas appeared more saturated than the smaller. He found the saturating effect of increasing the area greatest for violet and decreasing in the order, blue, green, yellow, orange, red. He even concludes that a color field is not fully saturated until it extends over the

whole field of vision. This can hardly be true, for an observer in a room with neutral tint surroundings illuminated with pure red light is not conscious of a saturated red color. Similarly if a white paper on a black velvet ground be illuminated by a moderately intense red light it will appear quite unsaturated owing to the lack of anything with which to contrast it in color. The loss in saturation appears to progress with time, no doubt largely due to 'adaptation.' Whether or not this adaptation is psychological or physiological there is a lack of agreement. However, the effect of area is of importance, although there is much work to be done in this field before definite conclusions can be drawn.

Another experiment of importance in viewing colors which is connected with the rate of growth of color sensations and, perhaps, to a slight degree, with chromatic aberration, is found in viewing a red piece of paper on a blue-green ground held at an arm's length under a moderate illumination. If the paper be moved back and forth without relaxing fixation at a point in the plane in which the card is moved, the red patch will appear to shake like jelly and will appear not to be in the same plane as the blue-green paper. Thus there are numerous visual phenomena associated with the appearance of colors.

42. *Illumination.* — It has already been shown that the maximum spectral sensibility of the eye shifts toward the shorter wave-lengths at low intensities (Purkinje effect #4, Fig. 2). Therefore colors ordinarily encountered appear to shift in hue under low illumination. For example, a green pigment appears to assume a more bluish hue as the illumination is greatly decreased. On referring to Fig. 2 it is seen that the relative values of luminous sensa-

tion produced by equal amounts of radiant energy depend upon the wave-length. A colored pigment has the ability to reflect certain proportions of the rays of various wave-lengths. The latter is a purely physical operation which remains invariable regardless of the intensity of illumination. However, the relative physiologic effect of the different rays change so that the maximum luminosity is produced by energy of a shorter wave-length at low intensities than at high illumination. By multiplying the reflection coefficients

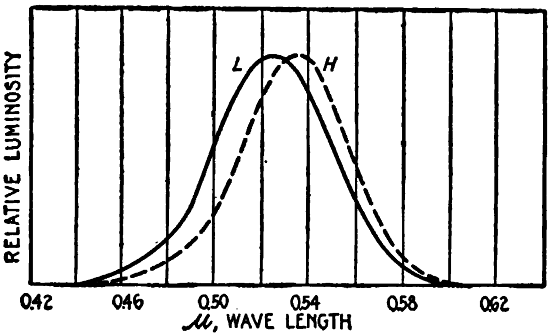


Fig. 79.—Effect of the intensity of illumination on the appearance of a pigment.

of a pigment for various rays by the luminosities of the corresponding rays at high and low intensities an idea of the shift of the dominant hue is obtained. This was done for a green pigment by using the luminosity curves in Fig. 2 for high (*H*) and low (*L*) illumination. The results plotted with equal maxima are shown in Fig. 79.

Colors appear more saturated at low than at high intensities of illumination. In fact, intense illumination causes colors to appear very much less saturated. For instance, a deep red object illuminated by direct sunlight is painted orange-red by the artist. The employment of this illusion is successful in conveying

to the observer the idea of intense illumination. Similarly colors appear more saturated when exposed only for a very short interval of time.

Quality or spectral character of light affects the appearance of colored objects very much. Except in very special cases a red fabric for example appears red because it has the ability to reflect chiefly the red rays (#12, Fig. 12). Such a fabric must appear black when viewed under an illuminant which contains no red rays. This is the case under the light from the mercury arc, which contains practically no visible rays longer than 0.579μ (yellow). It is a fundamental principle that, excepting in special cases, a colored fabric cannot appear the same under two different illuminants. Therefore two colors that appear alike under one illuminant will not match when viewed under another illuminant, unless the colors in each case show the same spectral character by spectrophotometric analysis. In other words, because the eye is not capable of analyzing a color spectrally, it is possible to produce colors which appear the same but whose spectral compositions differ. Such a match will not in general remain a match under another illuminant differing in spectral character. In Fig. 80 the effect of the illuminant upon the appearance of a colored pigment (purple) is shown diagrammatically. The relative luminosities (dotted lines) produced by the relative amounts of energy (full lines) of corresponding wave-lengths are shown for daylight in the illustration on the left. The result as shown by the dotted curve is to give to the pigment the appearance of a blue-purple. However, when this same fabric is illuminated by ordinary artificial light of continuous spectral character, the excessive amounts of energy of the longer wave-lengths and the defi-

ciency in short-wave energy as compared with daylight alter the spectral character of the light reflected (or transmitted) by the fabric as shown in the dotted curve on the right. The appearance under the artificial light is red-purple. It is difficult to distinguish a blue fabric as blue under ordinary artificial light owing to the scarcity of blue rays in most of the artificial illuminants. Of course a truly monochromatic pigment (if such existed) would not be

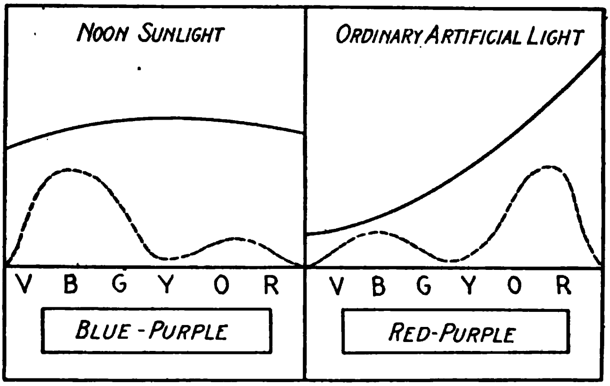


Fig. 80.—Illustrating why a purple appears differently under two different illuminants.

changed in hue under various illuminants but would be altered in brightness. In the special case where no energy existed in the illuminant of the wavelength corresponding to that reflected by the monochromatic pigment, the latter would appear black. However, no monochromatic colors are found in practise, but if pigments that were practically monochromatic existed very generally, a greater intensity of illumination would very often be required than at present, because such colors would reflect very little light. Pigments ordinarily encountered reflect considerable light, owing to the fact that they

reflect energy throughout an appreciable range of wave-lengths.

The spectral character of an illuminant not only influences the hue but also affects the brightness or 'value' of a pigment. Practically the whole series of Zimmerman papers were measured for their relative brightness with a reflectometer (Fig. 60) under illuminations respectively from an overcast sky and from a vacuum tungsten lamp operating at 7.9 lumens per watt. The data are given in Table XV, the cata-

TABLE XV

Effect of Spectral Character of Light on the Brightness of Colored Papers

Paper	Color of paper	Reflection Coefficient		Ratio $\frac{\text{R (Tungsten)}}{\text{R (Skylight)}}$
		Overcast sky.	Tungsten 1.25 w. p. m. h. c.	
a	Red-purple	0.16	0.23	1.44
b	Deep red	.14	.22	1.57
c	Red	.21	.31	1.48
d	Red	.19	.24	1.22
e	Orange	.38	.48	1.26
f	Orange-yellow	.60	.66	1.10
g	Yellow	.60	.65	1.08
h	Greenish yellow	.67	.70	1.04
k	Yellow-green	.46	.42	0.91
i	Dull green	.49	.45	0.92
q	Saturated green	.32	.24	0.75
n	Blue	.23	.17	0.74
o	Deep blue	.13	.09	0.69
p	Blue-purple	.14	.12	0.86
m	Gray-blue	.30	.25	0.83

logue designations of the papers being found in the first column. As would be suspected, the papers which have the ability to reflect the rays of longer wave-length predominantly appear relatively brighter under the artificial light. In other words their reflection coefficients are greater for the tungsten light

than for daylight. Those colors having the ability to reflect the rays of shorter wave-length predominantly, have relatively greater reflection coefficients for daylight; that is, they appear relatively brighter under daylight illumination. (See Figs. 113 and 117.) Thus it is seen that the spectral character of the illuminant has a great influence on the appearance of a colored object, inasmuch as it influences both the hue and brightness (value) very much.

Owing to the surface character of colored media the distribution of light is of some importance in the consideration of the appearance of colors. Few pigments are applied in such a manner as to be perfectly diffusing, therefore some light is specularly reflected without having penetrated the pigment. This light is unchanged by selective absorption and dilutes the light that is colored by penetrating the pigment and being selectively reflected. That is, when the light is distributed in such a manner that an appreciable amount is specularly reflected into the eye of the observer the color appears less saturated. In the extreme case of high specular reflection the pigment appears the same as a gray. A striking illustration of the effect of distribution of light is found in the case of the so-called changeable silks. Such fabrics have a nap, and when the fibers end in the direction toward the light the latter penetrates the fabric and is deeply colored by multiple selective reflections. The light that comes from other directions is more or less specularly reflected, thus undergoing less change by selective absorption, with the result that various portions of the surface appear differently. Adding to the foregoing another property of aniline dyes and the colors of changeable silks are accounted for. For instance, a dye which in solu-

tion appears pink or purple in color is often found to reflect green light predominantly in the solid state. Thus the specularly reflected light in the case of the changeable silk is sometimes roughly complementary to the light that penetrates the fabric and is returned after multiple reflections which in effect correspond to traversing a certain depth of an aqueous solution of the dye. A color will often appear different by reflection than when examined 'over-hand' by looking through the fibers by glancing along the surface at a grazing angle (#75).

43. *After-images.* — It has been seen that the retinal excitation requires appreciable time to decay after the stimulus has been removed. If the filament of an incandescent lamp be viewed for an instant and the eye be then closed, an image brighter than the surroundings will persist for some time. This has been called a positive after-image. Soon, depending upon the intensity of the stimulus, the image will reach a stage of decay when it appears darker than the surroundings. If the closed eyelid be illuminated the visual field will appear brighter than in the case where the eyelid is shielded from the light by the hand placed gently against it. In the former case the after-image will remain 'positive' a shorter time than in the case of the darker surroundings. The same will be found when viewing the after-image against various white or gray backgrounds with the eyelid open. The effect of the brightness of and exposure to the stimulus on the duration of the after-image is shown in Fig. 81. In this experiment the actual duration was somewhat longer than indicated, the criterion being the time after exposure that was required for the after-image to decay to a certain definite, though faint, appearance. The after-

images were found to go through a certain cycle of brightness and hue changes which were not recorded. The stimulus was a bare tungsten filament varied in brightness by a variable sectored disk which was rotated at a high speed. The brightness is given in terms of candles per square inch. The after-images were observed against a faint background produced by the illumination of the closed eyelid by a small amount of stray light in the room. The changes in

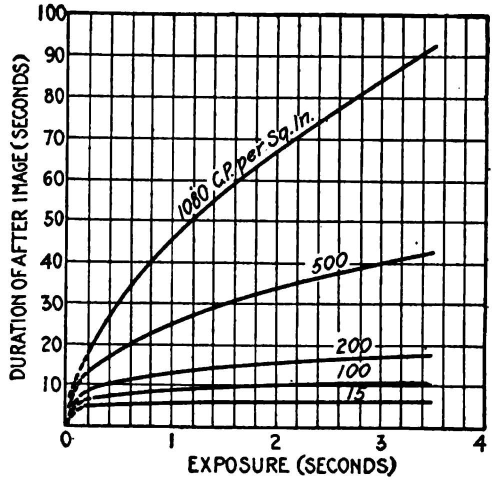


Fig. 81.—Effect of brightness on the duration of the after-image.

hue were not recorded. Positive after-images, obtained by fixating, for a few seconds, a white paper illuminated by sunlight, can be seen for a brief period, but they rapidly decay to a brightness lower than that of ordinary surroundings. In their decay they pass through a series of hues, namely blue-green, indigo, violet-pink, dark orange, etc., which are more or less definite. Helmholtz explains the colored after-images obtained in the above manner by assuming different rates of decay of the three hypothetical color sensations which are the basis of

the Young-Helmholtz theory of color vision (#47). The negative after-image is explained by Helmholtz as being caused by retinal fatigue, due to the original bright image of the white object. On stimulating the whole retina with white light the portion previously fatigued does not respond in the same degree as the unfatigued portions. It is difficult, however, to reconcile all the facts gleaned from studies of after-images with this fatigue hypothesis. Hering explains these phenomena by assuming that the retina is not fatigued, but that a metabolic change is aroused which is opposite in character to that produced by the original excitation (#49). After-images are also produced by fixating colored objects. For instance, if the object shown in Fig. 85 be fixated for a few seconds and the eye be turned toward a white surface, a pink after-image will be seen where the green had previously stimulated the retina. After-images viewed in this manner will usually appear approximately complementary in hue to the original stimulus. A striking illustration of approximately complementary after-images can be performed with the apparatus shown in Fig. 35. Here we have a large variety of colors, the corners of the triangle appearing red, green, and blue. After fixating the color triangle for a few seconds, if the lights be turned off and white light be permitted to illuminate the white opal-glass surface, approximately complementary after-images are seen. The experiment is striking, owing to the many colors present. In order to produce the complementary after-images in a striking manner, it is necessary to stimulate the retina with white light. If the experiment be performed in a dark room after the lights in the colored triangle are extinguished, the ordinary after-images will be per-

ceived, depending upon the color of the stimulus, its intensity, and other factors. After-images play quite an important part in vision, especially in viewing paintings and many other colored objects. For instance, if a blue skyline be viewed in juxtaposition with a green landscape, the natural shifting of the eye, even when attempting moderately to gaze steadily at the picture, will cause a shifting of the image of this dividing line upon the retina, with the result that the pinkish after-image due to the green stimulus (and likewise that due to the blue stimulus) will, in shifting above and below the horizon line, produce a vivid effect. Such phenomena often greatly add to the 'life' of a painting. After steadily fixating a colored object for some time the color appears to become less saturated, and often there is an apparent change in hue. If a small piece of black paper on a larger background of red be fixated for a few seconds and the black paper be suddenly removed without disturbing the fixation, in its place will be seen a red spot more luminous than the surroundings and of a more saturated reddish appearance. These experiments can be successfully performed with the Zimmerman colored papers.

Successive contrast further complicates the appearance of colors. After stimulating the retina with red light, if the eye be suddenly fixated upon a green color the latter will appear more intense or saturated in color for a moment than if the eye had not been previously stimulated by the red light. On alternating these colors by means of a rotating disk at a low speed very brilliant effects are seen. Such successive contrasts are of importance in the study and application of color science. For instance, in permitting the eye to rove over a painting or bril-

liantly colored rug the appearance of the various individual colors are influenced by the previous retinal stimulation. The phenomenon of after-images has been only briefly touched upon here. The many details connected with them serve to show how intricate is the reaction of the retina to light.

44. *Simultaneous Contrast.* — A detailed examination of the mutual effect of two visual excitations is difficult, although the fundamental principles are

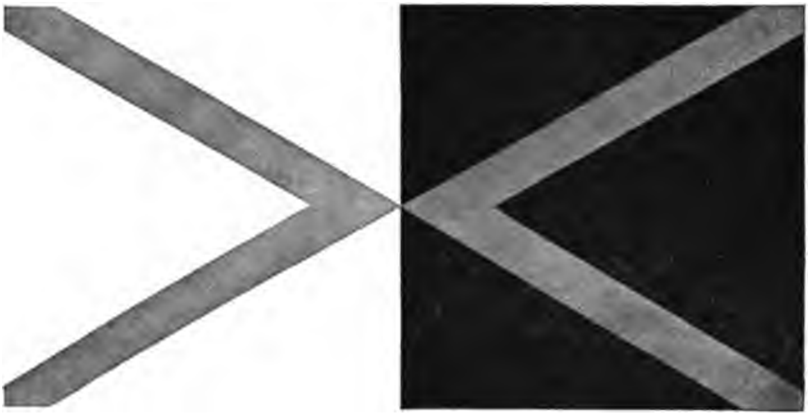


Fig. 82. — Showing the effect of simultaneous contrast. The V's are of equal brightness.

not difficult to demonstrate. On viewing a gray pattern on a black background it appears brighter than when viewed upon a light background. The illustration shown in Fig. 82 was originally made by cutting the two figures in the form of a V from the same gray paper. On placing them as shown — one on a black and one on a white ground — the one on the white ground appears darker than the other. The effect is so persistent that a much darker gray can be placed on the black background and yet it will appear brighter than the one on the white ground.

In fact it is practically impossible to make both appear alike by decreasing the brightness of the gray V on the dark ground. If several gray papers of different shades be placed as shown in Fig. 83, the edge of a lighter gray strip that is adjacent to a darker one will appear brighter than the other edge of the lighter gray strip. Such a specimen can be obtained by juxtaposing gray papers of different shades or by exposing a photographic plate in a very weak light by pulling out the slide of the plate holder a half-inch at a time at regular intervals. A print from a

Fig. 83.—Showing induction. Each band, though uniform in brightness, appears brighter at the right-hand edge.

successful negative will afford an excellent specimen for showing this phenomenon of induction. On rotating such a disk shown in *b*, Fig. 30, this phenomenon of induction can be demonstrated before a large audience. A striking demonstration of brightness contrast can be performed by viewing a gray paper through a hole in a white unilluminated screen. It appears very bright in contrast to the dark surroundings. However, on illuminating the white surroundings it is possible to make the former bright spot appear very dark by contrast. The demonstrations of color contrast are very numerous. M. E. Chevreul,[2] who directed the dyeing laboratory of the famous Gobelins many years ago, carried out very extensive researches on the effect of simultaneous contrast of colors as used in the textile industry. The

record of his experiments is monumental. Many have investigated the problem with the view of throwing light on color-vision theories, but many of the details garnered by the vast number of investigators remain unsatisfactorily explained.

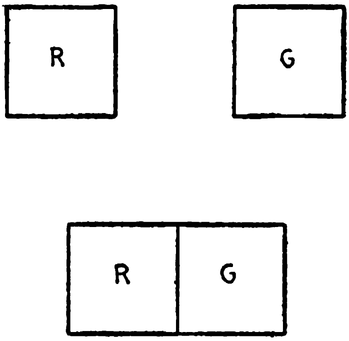


Fig. 84. — An arrangement for showing the reduction in the contrast effect by separating the two colored objects.

The intensity of the contrast effect diminishes rapidly on passing away from the point of maximum contrast. In Fig. 84 when two colors such as red and green are juxtaposed they appear accentuated in saturation and deeper in hue. In the case of these two colors they appear to move further apart in hue. When the two colors are separated as shown above, the contrast effect practically disappears. If a disk of green be placed on a larger disk of red the contrast is very effective but if the smaller disk is outlined by a black circle the effect is reduced. If a gray figure, as in Fig. 85, be placed upon a green background, the gray figure will appear of a pink hue. The contrast hue induced in this manner is approximately, though in general not exactly, complementary to the exciting color. If a sheet of thin white tissue paper be placed over the arrangement shown in Fig. 85, the hue induced in the gray paper will be considerably strengthened.

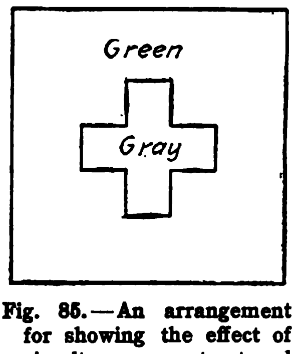


Fig. 85.—An arrangement for showing the effect of simultaneous contrast and after-images.

Colored shadows were noticed by such great colorists as Leonardo da Vinci. These are illustrated by casting the shadow of a pencil on white paper by light entering a window; only black and white contrast is seen. However, if from another direction light from an incandescent lamp be permitted to fall on the paper, another shadow is produced. If the two shadows are of approximately the same brightness, the contrast colors of the shadows are very striking. The white ground outside the shadows is receiving the mixed light from the two illuminants, while the shadow cast by daylight receives light from only the incandescent lamp and appears yellow. The other shadow receiving only daylight appears blue. Shadows in a landscape appear blue because they receive light from the sky, and they often appear more vivid owing to contrast. Hering devised a most striking demonstration of binocular contrast. Red and blue glasses were placed in front of the two eyes respectively. The glasses sloped away from the eyes from the nasal to the temporal side. This permitted a control of saturation by introducing a white image from the sides by reflection. A black stripe on a white ground is doubled by increasing or decreasing the ocular divergence. The observed ground appears spotted, alternately blue and red, and sometimes a purplish white, which is due to 'retinal rivalry.' The stripe seen through the red glass appears green and through the blue glass appears yellow.

Brücke, Helmholtz, and others contend that the contrast effects are not of a physiological nature, but rather 'errors of judgment'; that is, through the influence of an adjacent color our 'standard white' undergoes a change which alters our judgment. In

other words they claim the effect is of a psychological nature. These arguments have been repeatedly attacked and not without a considerable degree of success by Hering and others. For example, Mayer[3] devised methods for showing contrast color phenomena on surfaces large enough so that the colors could be matched by means of rotating color disks and thus he obtained quantitative measurements. He found that the subjective contrast colors were perceptible when viewed through a small opening for exposures as short as 0.001 second. They were also perceptible with instantaneous illumination from an electric spark, the duration of illumination in this case being of the order of one ten-millionth of a second. He concluded from this experiment that fluctuation of judgment was an untenable hypothesis for explaining subjective color contrast owing to the extremely short period of time of exposure.

On the other hand, Edridge-Green[4] contends 'that all our estimations of color are only relative and formed in association with memory and the definite objective light which falls upon the eye. In many of the most striking contrast experiments the color which causes the false interpretation is not perceived at all; for instance, if a sheet of pale green paper be taken for white, a piece of gray paper upon it appears rose colored, but appears colorless when it is recognized that the paper is pale green and not white.'

Thus the controversy continues. Many contradictory experimental data and opinions could be cited. Contrast may be due to unconscious eye-movements, to incipient retinal fatigue, to fluctuation or error of judgment, or to some other cause. Nevertheless there is no agreement as to the true explanation at the present time.

In Plate III are provided a number of arrangements which show the effects of simultaneous contrast — brightness and hue contrasts — and various mixtures of these. Some of these illustrate restful and 'lively' combinations of color. There will be found much of interest in this illustration upon carefully observing the various combinations alone and in comparison with adjacent ones. The four smaller squares in each row are identical in hue and brightness, which can be readily proved by the use of a

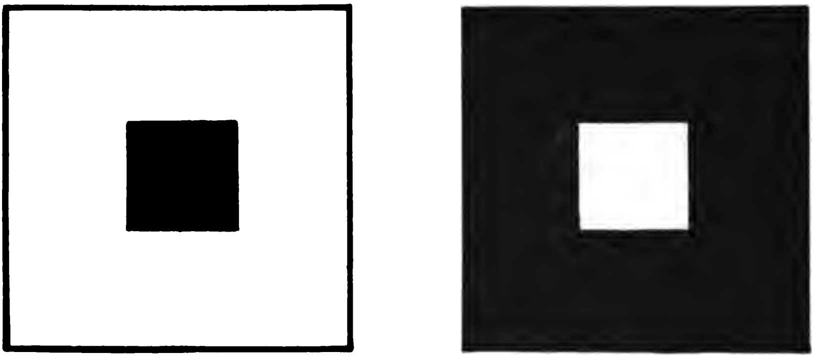


Fig. 86. — Illustrating irradiation.

mask. If this plate be covered with a white tissue paper some of the color contrasts are very striking.

45. *Irradiation.* — This name is applied to the phenomenon of apparent increase in size of objects as they are increased in brightness. For instance, the crescent of the new moon appears larger than the remainder of the disk. A filament of an incandescent lamp appears to increase in diameter as its temperature is raised from a dull red to its normal operating temperature. This effect has been attributed by some to a spreading of the retinal image on account of a stimulation of nerves outside its actual geometric boundary. Others attribute the effect to

the aberrations in the optical system of the eye. In Fig. 86 the inner white square appears larger than the inner black square under high illumination, yet both are identical in size. The phenomena of simultaneous brightness contrast is also evident, the white square amid black surroundings appearing brighter than the larger white square. Such effects are also perceptible with colored objects, as will be seen in Plate III.

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CHAPTER VIII

THEORIES OF COLOR VISION

46. Recorded writings, centuries before the beginning of the Christian era, contain speculations on the visual process. Alcmæon, Empedocles, Aristotle, Democritus, Anaxagoras, Plato, and Diogenes are among the early writers and philosophers who presented views on the nature of light and colors and on the process of vision. However, their speculations — which can hardly be considered otherwise, owing to lack of experimental data — are of little value since the modern development of the sciences. Color vision is largely physiological and psychological. The process of vision involves the physical cause, the physiological retinal process, and the psychological elements in the experience of sensations. As the knowledge of the three sciences involved in the process of color vision developed, theories of color vision became more intricate. In fact the various theories which are given credence at the present time are found on strict analysis to include in varying degrees the physiologic process of vision, color vision, and the nature of perception. A theory of color vision must include all the foregoing factors, yet the dominating influence of one of these is usually perceptible in a given theory. In this chapter it is proposed to set forth briefly the latest theories which pertain to the subject of color vision.

47. *Young-Helmholtz Theory.* — Thomas Young is credited with the conception of the three-color

theory, but it seriously lacked experimental foundation until after the epoch-making work of Helmholtz,[1] and since that time it has become known as the Young-Helmholtz theory. The hypothesis is that color sensations depend upon the action of three independent physiological processes involving three substances or sets of nerves. This theory approaches the matter chiefly from the side of physics; that is, the facts of color-mixture are used in building up the theory. There is no anatomical evidence that the three substances or sets of nerves are present. The primary sensation curves shown in Fig. 53 were determined by Koenig by being built up from experimental data; these have been proposed as representing the three independent processes. They are plotted so as to enclose equal areas on the assumption that the sensation of white results from the stimulation of equal amounts of the three primary sensations. It is noted that spectral hues involve more than one of the primary sensations.

This theory explains the main facts of color vision, although many details uncovered by experimenters have not yet been reconciled with it to the entire satisfaction of many scientists. After-images are explained by assuming fatigue of one or more of the processes in varying degrees. For instance after fatiguing the eye to green light a white surface appears an unsaturated purple — pink. Many of the observed facts in the study of after-images are only approximately conciliable with this theory. The problem of simultaneous contrast offered no difficulties to Helmholtz, because he assumed that the phenomenon is the result of 'false judgment.' While it may be purely psychological, it appears probable to some that it is actually physiological in nature,

one part of the retina being influenced by stimulation of another region. Color-blindness is explained by assuming that one or more of the three processes are absent, the remaining process (or processes), if necessary, being assumed to be 'redistributed' to some extent. This theory has some advantages in explaining the cases of red and of green blindness by assuming the absence of the corresponding process and if necessary a slight modification of the other two. It fails to explain total color-blindness, however. When it is attempted to reconcile this theory with all the observed facts, one finds a highly complex state of affairs. Such a discussion is outside the scope of this chapter, therefore only the main theories and facts will be presented. Extended discussions will be found in the treatises referred to at the end of this chapter. The Young-Helmholtz theory satisfactorily explains the observed facts of color-mixture, but the chief objection to the hypothesis as it exists at the present time, is that it fails to explain many other facts, such as those of contrast.

48. *'Duplicity' Theory.* — This theory, which attempts to differentiate colorless and color vision, is chiefly associated with the name of Von Kries. It is based upon anatomical evidence of the existence of 'rods' and 'cones' in the retina. The former are assumed to be responsible for achromatic sensations and the latter for both achromatic and chromatic sensations. The rod action is supposed to be largely responsible for light sensation at twilight illumination and is in general more responsive to rays of shorter wave-length. The cones, however, are supposed only to act under stimuli of brightnesses represented by the range above twilight illumination and not to be greatly increased in sensitiveness by dark

adaptation. Examination of the retina shows that the cones alone exist in the very center of the retina, the fovea centralis, and rods appear just outside of this and predominate in the outer zones. The chief observed facts that this theory explains fairly satisfactorily (perhaps because it was chiefly built up from these facts) are (1) colorless vision over the whole retina in dim light, for instance in moonlight, (2) the decreased sensitivity of the fovea in twilight, (3) the shift in the maximum of the luminosity curve of the eye (Purkinje effect) at low illumination, (4) the absence of such a shift for foveal vision, (5) no achromatic threshold is found for any light for foveal vision, (6) no achromatic threshold for red light for any region of the retina, and (7) colorless vision over the whole retina in the case of the totally color blind. Some of the experiments with color-blind eyes further support the theory. For instance the luminosity curve for a totally color-blind eye at ordinary illuminations is similar to that for a normal eye for twilight vision. There are also evidences of diminished foveal sensibility, abnormally good vision in twilight, and decreased ability to fixate small objects with color-blind eyes. Further support is found in the presence of rods almost exclusively in the retinæ of such nocturnal animals as the owl and bat. The supporting evidence in general is represented by more dependable and convincing data than in the case of any theory of color-vision. The 'duplicity theory' does not attempt to explain color-vision, but is of interest here because of the attempt to separate vision into chromatic and achromatic processes.

49. *The Hering Theory.* — The principal foundation of this theory [2] consists of facts such as those of contrast, and the apparent simplicity of black,

white, and yellow as well as red, green, and blue. Hering assumes there are six fundamental sensations coupled in pairs, namely, white and black, red and green, yellow and blue. In order to account for these six fundamental sensations he assumes the presence somewhere in the retinocerebral apparatus of three distinct substances. Each substance is capable of building up (anabolism) or of breaking down (katabolism) under the influence of radiant energy or its effects. The building up of the black-white substance causes a sensation of blackness, and the breaking-down of this substance, a sensation of whiteness. Likewise anabolism of the red-green substance is connected with the sensation of green and katabolism with red sensation. Similarly, the building up of the third substance produces blue, and the breaking down is associated with yellow sensation. For example, red rays cause a breaking down of the red-green substance, with the result that red sensation is experienced. It is claimed by many that this theory has an advantage over the Young-Helmholtz theory, because it deals more directly with the sensations of color. The theory has many enthusiastic supporters and is fully as favored in this respect as its most formidable rival. A favorite argument in support of it is the observed fact that yellow appears to be a primary color because there is no simultaneous suggestion of both red and green in a yellow made by mixing these two colors (Fig. 17). Many observed facts concerning after-images agree with the theory. For example, if the eye be stimulated by blue rays, anabolism will take place in the yellow-blue substance and an accumulation of the substance results. If now yellow rays are permitted to stimulate the same area of retina, the break-

ing down of the yellow-blue substance proceeds at a greater rate and the sensation is greatly augmented. Conversely yellow decreases the amount of substance and increases the rate of anabolism under the subsequent stimulation of blue rays. Positive after-images are explained by assuming a continuation of the anabolic (or katabolic) change for a brief period owing to chemical inertia. All the general phenomena of after-images are explained satisfactorily, but as in the case of the Young-Helmholtz theory, details are troublesome. Some of the data on color-blindness readily support the theory, but the latter must be modified in order to explain other data. Donders[3] and others conclude that the Young-Helmholtz and Hering theories, having been formulated from different points of view, have arrived at different conclusions and that both are in part correct. This is a rather safe conclusion, but nevertheless an important one, inasmuch as they are both thus stamped with the partial approval of scientists highly familiar with the subject.

50. *Ladd-Franklin Theory.* — In this theory[4] the rods and cones are used. Colorless sensations white, gray, and black, are assumed to be caused by a primitive photo-chemical substance which is composed of many 'gray' molecules. These exist in their primitive state only in the rods, but upon dissociation they cause the colorless sensation. In the cones the gray molecules undergo development and for some reason only a portion of the molecule becomes dissociated by rays of a given wave-length or color. The evolution of the gray molecule is assumed to take place in three stages diagrammatically shown in Fig. 87. In the first stage the gray molecule exists, but is so constructed that it is disintegrated by light of

all colors, thus producing a white or a gray sensation. In the second stage the molecule has become more complex and contains two groupings. The dissociation of one of the latter causes a yellow sensation and the other, blue. Their simultaneous dissociation causes a sensation of white or gray. Molecules are assumed to exist in this stage in the outer zone of the retina, where neither red nor green can be perceived as such. In the third stage the yellow grouping is divided into two new combinations, the dissociation of one giving rise to a red sensation, the other producing a green sensation. If the red and green are dissociated simultaneously, yellow sensation results, while all three (red, green, and blue) together produce gray. There is much of interest in this theory, and it appears to explain many observed facts satisfactorily.

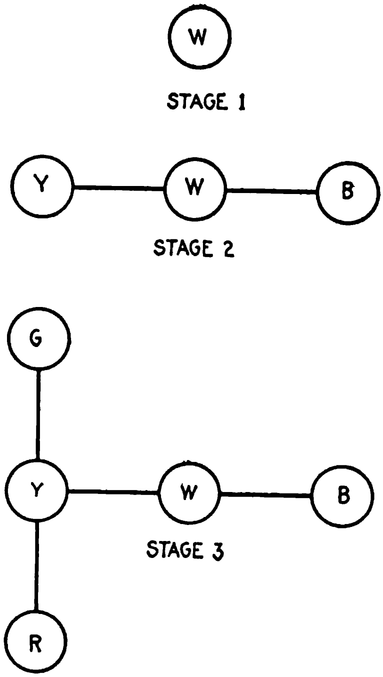

Fig. 87.—The evolution of the Ladd-Franklin gray molecule.

51. *Eldridge-Green Theory.*—Boll discovered a substance diffused in the retina which has been named visual purple. This discovery gave rise to hopes that a photochemical theory of vision would explain the observed facts, inasmuch as the visual purple was found to be sensitive to light. However, after the elaborate work of Kühne the visual purple lost much of its significance in this respect. If an

eye which has been unexposed to light for some time be cut out in a room illuminated by means of a dim red light, on removing the retina it appears a purple color under ordinary light. The color fades rapidly on exposure to ordinary intensities of illumination, passing through red and orange to yellow, finally disappearing. The yellow appearance is supposed to be due to the formation of another pigment, the visual yellow. The appearance of the preceding stages is thought to be due to mixtures of the visual purple and visual yellow in various proportions. It apparently has been established that normally the visual purple is confined to the outer portions of the rods. It is extracted readily by a watery solution of bile salts. Spectroscopic examination of this solution shows it to have a maximum absorption for yellow-green rays and a minimum for red rays and is bleached by the rays in about the proportion that it absorbs them. The visual purple is so sensitive to light that pictures of very bright objects have been seen in purple and white on retinæ of the eyes of animals. Such experiments have been performed by exposing an eye extracted from an animal which has been kept in darkness for some time.

Many attempts have been made to weave the visual purple into a theory of vision. Edridge-Green [5] has done so, as briefly outlined below. He assumes 'that the cones of the retina are insensitive to light, but sensitive to the changes in the visual purple. Light falling upon the retina liberates the visual purple from the rods, and it is diffused into the fovea and other parts of the rod and cone layer of the retina. The decomposition of the visual purple by light chemically stimulates the ends of the cones (probably through the electricity which is produced)

and a visual impulse is set up which is conveyed through the optic nerve to the brain.' He further assumes that 'the visual impulses caused by the different rays of light differ in character just as the rays of light differ in wave-length. Then in the impulse itself we have the physiological basis of the sensation of light, and in the quality of the impulse the physiological basis of the sensation of color.' He also assumes 'that the quality of the impulse is perceived by a special perceptive center in the brain within the power of perceiving differences possessed by that center or portion of that center. According to this view the rods are not concerned with transmitting visual impulses, but only with the visual purple and its diffusion.' On this theory he attempts to explain all the observed facts encountered. He concludes the paper, from which the foregoing is quoted, by stating that 'I am not aware of any fact which does not support the theory.' Needless to say, however, there are those who entertain a different opinion on this last and other points.

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CHAPTER IX

COLOR PHOTOMETRY

52. The relation between radiation of various wave-lengths and luminous sensation has long been the subject of investigation; but, notwithstanding the extensive data obtained, there is no general agreement as to a method that yields correct results. Much of the early data is practically useless at the present time, owing to the lack of control of various influential factors, due to the absence of definite knowledge regarding their ability to influence the judgment of brightness. This data of course has served well in lighting the pathway of investigation.

From foregoing chapters it has been seen that the size of the photometric field, owing to the variation of retinal sensibility to colored light, is of importance in color photometry. Due to the Purkinje phenomenon the brightness at which measurements are made also affects the results. In this connection it should be noted that the brightness of the photometric field as seen by the eye is sometimes greatly reduced by absorption of light in the optical path and by a small ocular aperture or artificial pupil of the instrument. Other factors, such as the adaptation of the eye and the character of the surrounding field, are influential. Most important is the method, for no two methods yield exactly the same results. It is well to remember that the brightness of a colored area is so influenced by its environment that its determination, in comparison with a standard in an isolated photometric

field, is not in general a measure of its brightness as it appears in another environment. Therefore the photometry of colored surfaces yields measurements of the brightness in terms of the particular standard used and the results depend upon the hue, saturation, and brightness of the comparison field, the surroundings, the condition of the eye, and the photometric method used.

53. *Primary Methods of Photometry.* — A method of photometry should ordinarily have for its object the measurement of the illuminating value of the illuminant with respect to its ability to make objects visible by reflected or transmitted light. The method of visual acuity has been proposed and used by some for the measurement of illumination. Obviously such a method determines the defining power of the illuminant or of the light reflected or transmitted by an object. The criterion of such a method is usually the discrimination of fine detail or the adjustment of the illumination so that the detail appears to be equally legible as compared with a standard. In general this method is quite insensitive, and the results are greatly dependent upon fatigue and the state of adaptation of the eye. However, there is another complication, that of the spectral character of light. The experiments of the author described in #37 showed that a reduction in the amount of illumination or brightness of the acuity test object, when accompanied by certain changes in the spectral character of the illuminant, sometimes results in an increase in visual acuity. From these experiments it is seen that the method of visual acuity cannot be depended upon to determine the relative illuminating values of illuminants or of lights altered in spectral character by reflection from colored surfaces.

The visual acuity method is valuable in many cases, but it must be understood that a large amount of our seeing does not include the perception of fine detail at the limits of discrimination, but only requires the recognition of relatively large surfaces through differences in color and brightness. Even reading under ordinary conditions does not involve visual acuity at the limit of discrimination, for the illumination is usually far above that necessary to distinguish the type, and it has been shown that in reading the eyes recognize characters in groups, travel by jumps, and come to rest only a few times during their progress across a page.

At one time the critical frequency method was looked upon as a possible solution of the problem of color photometry. It was shown in #38 (Figs. 75 and 76) that if a brightness be alternated against darkness there is a certain minimum frequency of alternation, called the critical frequency, at which flicker just disappears. In general, it has been found that the critical frequency varies directly as the logarithm of the illumination or brightness of the test surface. Thus plotting these two factors yields a straight line, the slope of which is different for lights of different colors. The slope of this straight line changes abruptly at a very low illumination (thought by some to be the point at which the cones just cease to be sensitive to light) for lights of all colors with the exception of red. By this method two surfaces were assumed to be equally bright when their critical or vanishing-flicker frequencies were equal. The method has proved too insensitive for practical use and too susceptible to various physiological factors, such as fatigue and adaptation.

The ordinary direct comparison or equality-of-

brightness method is claimed by many to involve the only true criterion for the measurement of brightness. Others claim that its shortcomings have disqualified it for use in the photometry of lights of different colors and have accepted the flicker method. The latter method, which is in high favor for color photometry, has not been *proved* to measure the true brightness of a colored surface — if there be such a thing. Nevertheless, the uncertainties in the measurements by the direct comparison method has brought this ordinary method into disfavor with many photometricians for the photometry of lights differing in color. The flicker method involves the alternation of two brightnesses — the standard and the unknown. A match is made with this instrument by altering both the brightness of the field due to one of the sources and the frequency of alternation. The two brightnesses are considered equal when the frequency of alternation is such that a slight change of either illumination produces a just perceptible flicker. When there is no color difference between the two brightnesses being compared, the theoretical frequency should be zero, but owing to imperfections in the photometric apparatus this condition is never obtained. The flicker photometer is based upon the fact that color difference is eliminated by mixing the two brightnesses by persistence of vision, the color flicker apparently disappearing before the brightness flicker. Numerous instruments have been devised for this purpose, but all involve this fundamental principle. No extended comparative study of flicker photometers has been made, although it is possible that instruments differing in design might yield different results. For instance, in many instruments the stimulus changes abruptly from one color to another, but in

some the stimuli dissolve into each other. Whether or not such instruments yield different results is a question to be solved by further investigation.

To summarize, the methods of visual acuity and critical frequency are impracticable owing to their

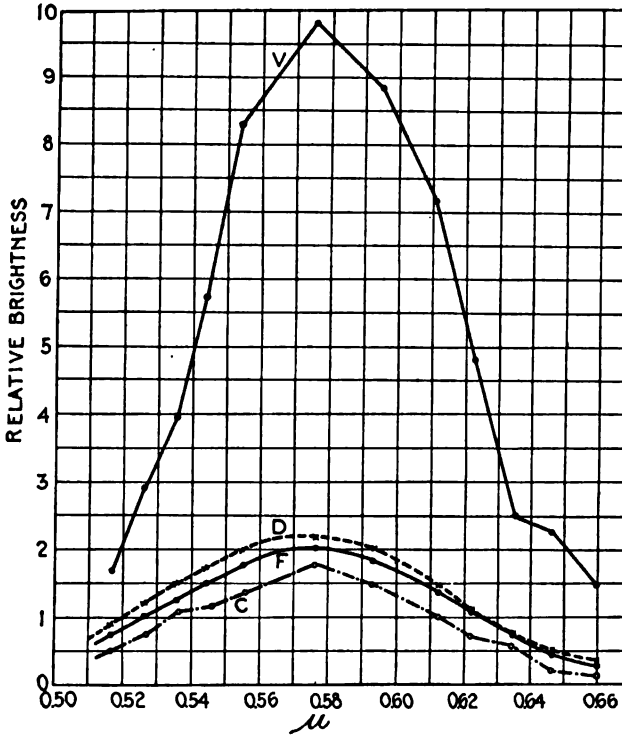

Fig. 88.—The results of four methods of photometry (Ives).

extreme insensitiveness and the influence of eye fatigue and adaptation. The influence of the spectral character of light further complicates the visual acuity method. The direct comparison method, though claimed by many to yield measurements of 'true' brightness is unpopular, owing to the uncertainties in the measurements. The flicker method, however, owing to its elimination of color difference and high

sensibility, had won many ardent supporters even before extensive investigations of the method had been made.

In Fig. 88 are shown data obtained by Ives[1] with the four methods. In each case the standard was the total light from a tungsten lamp. Spectral colors were compared with this white standard. Curve *V* was obtained by the visual acuity method; *D*, by the direct comparison; *F*, by the flicker; and *C*, by the critical frequency method. If the four methods gave identical results, the curves would coincide. The general shapes and positions of the maxima are similar, but the areas under the curves are very different. The enormous area under curve *V* is in accord with the previous work of Bell[2] and of Luckiesh,[3] which showed that acuity was much better in monochromatic light than in light of extended spectral character.

54. *Secondary Methods of Color Photometry.*— Various schemes have been proposed and developed for eliminating color difference in heterochromatic photometry, such as the use of colored filters, and physical and chemical photometers used with filters that properly weigh the energy of various wave-lengths according to their light-producing effects. Among the latter possibilities are the radiometer, thermopile, selenium cell, photo-electric cell, and photographic plate. Obviously, in order to reduce measurements to absolute values, the transmission coefficients of the colored filters must be determined by some acceptable method. Likewise, determinations of the relation between radiation of various wave-lengths and the corresponding luminous sensations and of the sensibility of the instruments to energy of various wave-lengths must be made before

the results obtained with the selenium cell, the radiometer, filters, etc., are useful in measuring brightness.

Crova [4] suggested as a method of comparing lights possessing continuous spectra, but differing in color, the determination of their intensities at one wave-length, 0.582μ. The lights to be compared in this manner must not differ much in spectral energy distribution from the black body. Rayleigh,[5] Nernst,[6] Fery and Cheneveau,[7] Lucas,[8] Rasch,[9] and others have made various applications and modification of Crova's original proposal. The filter used by Crova consisted of an aqueous solution of anhydrous ferric chloride (22.321 grams) and crystallized nickelous chloride (27.191 grams), the total volume being 100 c.c. at 15° C. A thickness of 7 mm. of this solution was used which transmits energy from 0.63μ to 0.534μ with a maximum of transmission at 0.582μ, the wave-length which Crova found to be satisfactory for carrying out his proposed scheme. Ives [10] tested Crova's method by comparing the luminous intensities of a tantalum and a carbon incandescent lamp at various wave-lengths. He found that the wave-length for such a comparison lies between 0.56μ and 0.58μ, depending on the range of temperature. The latter wave-length was found to hold best of all within the limits of temperature represented by ordinary incandescent lamps of that time. Twelve years ago Fabry [11] recommended the use of two or more colored solutions for eliminating color difference, having first calibrated these solutions for thickness and transmission by an acceptable method. Aniline dyes were not used, because of the need for definite and reproducible solutions. By using two solutions, *A* and *B*, he was able to match the Carcel lamp with almost any illuminant. The solutions were made as follows:

A. Crystallized copper sulphate.................1 gram
Commercial ammonia (density 0.93)..........100 c. c.
Water sufficient to make one liter.

B. Potassium iodide.........................3 grams
Iodine.................................1 gram
Water sufficient to make one liter.

Ives and Kingsbury [12] have recently investigated the problem of obtaining suitable solutions that would eliminate color difference after the manner proposed by Fabry. They developed a yellow solution containing 100 grams of cobalt ammonium sulphate, 0.733 grams of potassium dichromate, 10 c.c. of 1.05 sp. gr. nitric acid, and distilled water to make one liter at 20 deg. centigrade. The method of preparation is considered very important and is presented in detail in the original paper. Of course a given depth or concentration of the solution has a different transmission for illuminants of different spectral character. The transmission values were determined by means of a flicker photometer by averaging the results obtained by specially selected observers. The transmission of the solution was found to vary considerably for different temperatures and the character and cleanliness of the glass sides of the containing cell were found to be of considerable importance. It was found possible to eliminate color difference in comparing many illuminants with the carbon lamp standard by placing the solution on either one side or the other of the photometer.

Many have used aniline dyes and colored glasses. In practical photometry the use of colored glasses appears to be satisfactory for a large amount of work. The carbon lamp operating at about 4 w.p.m.h.c. is the present standard of luminous intensity. Properly

tinted bluish glasses used with this standard will eliminate the color difference when comparing tungsten lamps with it. The transmissions of the tinted glasses can be obtained by averaging the determinations of a large number of observers, using the direct comparison method. Such a procedure is being used successfully in several laboratories for the above work where the color difference is not excessive. However, it is not a solution of the general problem of color photometry.

Houston [13] in 1911 proposed the use of a filter composed of two solutions — copper sulphate and potassium dichromate — for closely approximating in transmission the luminosity curve of the eye, this filter to be used with an energy-measuring instrument. Köenig's visibility data were used as a basis for developing the solution. A proper solution would transmit rays of various wave-lengths in the proportions corresponding to the relative light-producing values of the various rays. It is necessary to cut off both the infra-red and ultra-violet rays and to reduce the visible rays in just the correct relative proportions so that an energy-measuring instrument (bolometer, thermopile, or radiometer) will record data proportional to the luminous intensity. A disadvantage of such instruments is found in their extreme sensitiveness to outside disturbances. For instance, the galvanometer used in the procedure must be of a high order of sensibility and therefore must be set up where it will be free from mechanical and magnetic disturbances. Karrer,[14] recently following Houston's lead, similarly employed the visibility data obtained by Ives. By using three solutions he was able to produce a screen whose transmission curve closely approached this luminosity curve of the

eye. The solutions were made by dissolving (1) 57.519 grams of cupric chloride, (2) 1.219 grams of potassium bichromate, and (3) 9.220 grams of ferric chloride, each in one liter of water. A triple cell was used, each compartment being 1 cm. thick.

The selenium cell has been used for stellar photometry and for other special work, owing to its change in resistence on being illuminated. However, it has not yet found a place in color photometry, because at present it is too erratic and undependable.

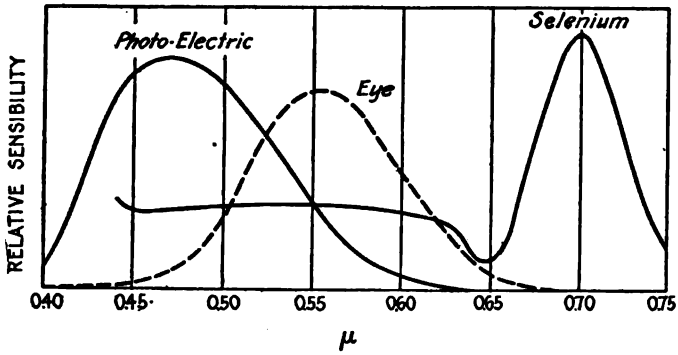

Fig. 89.—Spectral sensibilities of selenium and photo-electric cells compared with the spectral sensibility of the eye.

Its sensibility to energy of various wave-lengths appears to depend upon the method of making the cell, and is in general far different from that of the eye. A sensibility curve is shown in Fig. 89, compared with the luminosity curve of the eye. The maximum change in resistance is usually due to energy of the longer visible wave-lengths. Obviously a filter that properly weighs the energy of various wave-lengths according to its light value and to the spectral sensibility of the cell, must be used for the photometry of illuminants of extended spectral character.

The photo-electric cell has been used in special cases of scientific investigation for detecting the

presence of radiant energy. Surfaces of potassium, zinc, and other elements and compounds in vacuo exhibit the property of emitting electrons when illuminated. The maximum effect is usually found in the short-wave visible region, as illustrated by a sensibility curve of a photo-electric cell, shown in Fig. 89. As in the case of the selenium cell, the photo-electric cell is too erratic at the present time to be adopted as a means of photometering lights of different colors. The strengths of the electronic currents measured by means of a sensitive electrometer or galvanometer afford a measure of the relative intensities of the illumination of a given spectral character when the characteristics of the cell are shown; that is, when the relation between the intensity of illumination and the photo-electric effect is known. Lights differing in spectral character cannot be compared by means of the photo-electric cell unless a correcting filter is used after the manner necessary with the selenium cell.

The photographic plate affords another possible method for the photometry of lights of different color, but its general adoption is discouraged, owing to lack of uniformity of the emulsion both as to thickness and sensibility. Some of the difficulty could be obviated by using plates made of plate glass. The panchromatic plates must be used, because the ordinary plate is not appreciably sensitive to rays of longer wave-length than 0.48μ, the maximum of sensibility being in the extreme violet region of the spectrum. The relative sensibility of a certain commercial panchromatic plate, for equal amounts of energy of various wave-lengths, is shown in Fig. 90 compared with the spectral sensibility of the eye. In order to make the plate record the values of col-

ored brightnesses as determined with a flicker photometer, an accurate filter was made which consisted of æsculine, tartrazine, rhodamine, naphthal green, and glass three-eighths of an inch thick. How nearly this filter performs its intended purpose is shown in Fig. 91 by the circles in comparison with the luminosity curve of the eye which is represented by the full line curve. This filter was used with the pan-

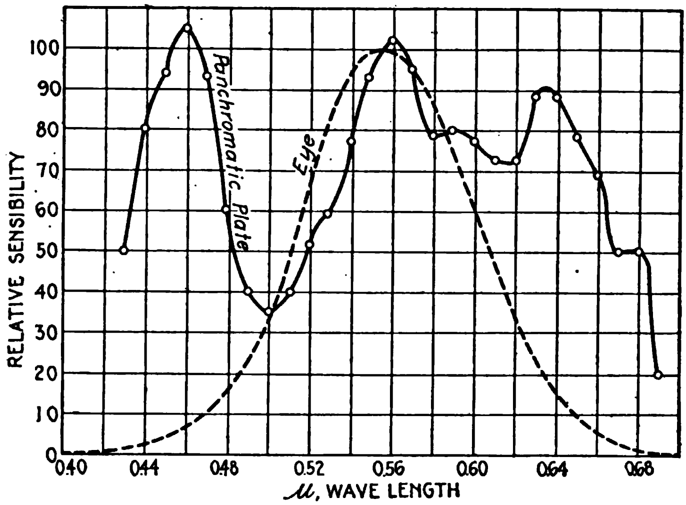

Fig. 90.—Spectral sensibility of a panchromatic photographic plate.

chromatic plate considered above, for which it was made by Ives and Luckiesh[15] for various photometric problems. In using the photographic plate for photometric purposes it must be remembered that, in general, the product of intensity of illumination and time of exposure is not a constant for equal photographic effect. The relation between exposure and intensity of illumination for a constant photographic effect as discovered by Schwartzchild is $It^p = iT^p$ where I and i are the larger and smaller intensities and T and t are the larger and smaller periods of

exposure. The value of p varies with different plates, generally lying between 0.75 and unity. The manner of development, the temperature, and other obvious factors influence the results so that the photographic method becomes unattractive except for special problems. As already stated, the use of these so-called physical or chemical photometers, while obviating color difference in practise, does not preclude the necessity of establishing the relation between luminous sensation and radiation of various wave-lengths by an acceptable method of color photometry.

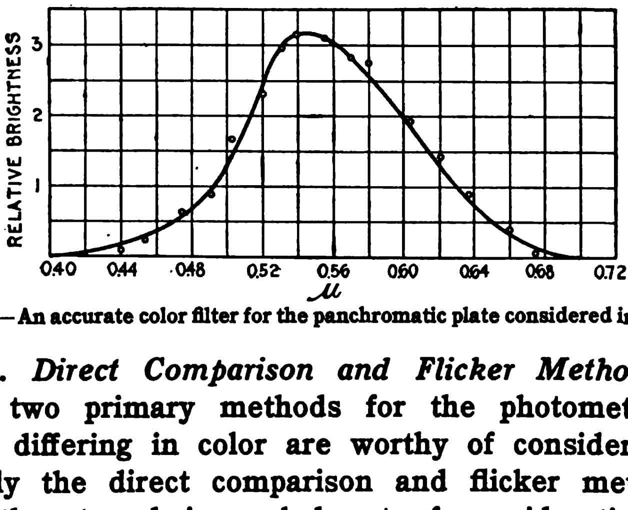

Fig. 91.—An accurate color filter for the panchromatic plate considered in Fig. 90.

55. *Direct Comparison and Flicker Methods.*—Only two primary methods for the photometry of lights differing in color are worthy of consideration, namely the direct comparison and flicker methods, the other two being ruled out of consideration for reasons already given. These two methods have been compared by many observers, but much of the work is so incomplete that it yields little data for a thorough comparison. It is desirable that the method finally acceptable for photometering lights of different colors should measure light-value with the same order of definiteness as other physical measurements are obtained.

Dow[16] compared these two methods by using

colored lights produced by means of red and green glasses at different intensities and with different field sizes. He found with the direct comparison method that the ratio of the red to the green brightness decreased with decreasing illumination, the decrease being rapid below 0.3 meter candle,—the well-known Purkinje phenomenon. With the flicker method this decrease was slight. With a small photometer field the change in the ratio of red to green was considerably less. In general Dow's results indicate that the flicker method is less influenced by the size of the field or by a change in the illumination than the direct comparison method.

P. S. Millar [17] compared mercury vapor arcs with incandescent lamps over a wide range of illuminations. The Purkinje phenomenon was in evidence in the direct comparison measurements but absent in the results obtained with a flicker photometer. In other words, with the former method the apparent brightness of the side of the photometer field illuminated by light from the mercury arc did not decrease as rapidly as the brightness of the other side illuminated by light from an incandescent lamp, as the illumination decreased. Stuhr [18] compared the four methods—namely, visual acuity, critical frequency, direct comparison, and flicker. He found the critical frequency and flicker methods to yield identical results, but these differed from the results by the other two methods. Various physiological factors, such as field size and illumination, were not considered.

Ives [19] carried out an extensive series of investigations which represent the most elaborate and thorough work yet done on the problem. He concluded that the flicker method is more sensitive than the direct comparison method and that the results

are more reproducible. He discovered that the flicker method exhibited a 'reversed Purkinje effect' and found, as other investigators had, that the two methods yielded different results in general, but concludes that the flicker method yields, under certain specified conditions, a measure of true brightness. Much evidence obtained throughout these investigations and some obtained by the author and others point favorably to the flicker method as the best method of photometry. However, notwithstanding the extensive investigations, some take the stand that the case has neither been decided against the direct comparison method nor in favor of the flicker method. This conclusion is perhaps justifiable. However, considering the unsatisfactoriness of the former method, there is considerable virtue in the adoption of the latter method with its many satisfactory features in default of a method which has been definitely proved to yield the desired measurements. Ives in his early papers did not emphasize the differences in the results obtained by the two methods. His results were plotted in the form of luminosity curves of the eye, so that without careful inspection, the results by the two methods, under certain conditions of high illumination and small field size, do not appear to differ greatly. In order to determine the magnitude of these outstanding differences the author [20] carried out an investigation, a portion of the results (*L*) being plotted in Fig. 92. Red and blue-green lights were used. The ratio of the intensity of the red to that of the blue-green light is plotted for a wide range of illuminations. The illumination values are those obtained with the flicker photometer and a standard tungsten lamp, but are not corrected for the absorption of the photometer, which, owing to

a complex optical path, was considerable, or for reduction due to the small artificial pupil. It is seen that the flicker method exhibits a reversed Purkinje effect and the direct comparison method the true Purkinje effect, and further that the ratio of the red to the blue-green brightness obtained by the direct comparison method is only about 62 per cent of that obtained by the flicker method for

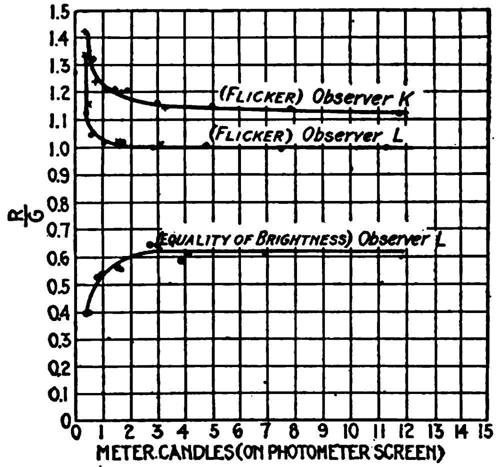

Fig. 92.—Results by flicker and direct comparison photometers, illustrating differences including the Purkinje effect and a reversed effect.

a large range of illuminations. The results as to the reversed Purkinje effect were verified in general by another observer (*K*). It is seen that he did not obtain the same results as the author, even with the flicker photometer, by about 13 per cent. A similar difference, though in general not as great, is found in Ives' data when the lights of the corresponding dominant hues (0.64μ and 0.52μ) are compared, even though in his measurements the spectral colors were always balanced against a white light. The same extreme difference in the results by the two

methods was confirmed by the writer using the same glasses a year later. The field size in the foregoing experiments was rather large — about ten degrees — but a large difference persists even with smaller fields, though not to such an extent.

Morris-Airey [21] suggested that the differences between the two methods might be due to the different rates of rise of the sensation with different colors. The author [22] studied this factor and showed that the maximum of a flickering red light was considerably greater than that of the blue-green light for a large range of flicker frequencies when the brightnesses of the two lights were those obtained by a direct comparison balance. This in itself did not prove which, if either, is the correct method. However, another experiment was performed which is perhaps as convincing as any yet performed in indicating that the flicker photometer when properly used is inappreciably influenced by the different rates of growth and decay of color sensations. Lights differing greatly in spectral character, but alike in hue, were compared by the two methods and identical results were obtained. Two yellow lights were obtained by means of filters of aqueous solutions of potassium dichromate used before a tungsten lamp. In one of the solutions was dissolved some neodymium ammonium nitrate, which absorbed all the spectral yellow. The two lights now nearly matched in hue and were readily brought to an exact color-match by altering the concentration and by adding a little ordinary yellow or orange dye to one solution. The spectral characters of these two lights are shown in *c* and *d*, Fig. 17. Two 'white' lights were also compared, one consisting of the total light from a tungsten lamp, the other being made up of narrow regions

of the spectrum, respectively in the red and blue-green. In both cases no difference in the ratio of the intensities of the two lights of the same color was detected in the results by the two methods, the accuracy being well within one per cent. It was also shown that red and blue-green lights add, whether by direct superposition or by alternately flickering them as in the flicker photometer, when the flicker is not more than barely apparent.

Further investigations may show that the flicker photometer is influenced by the different rates of growth and decay of color sensations, but the foregoing experiments indicate that such influence is slight. Ferree [23] has attacked this problem and has reported some interesting preliminary results. The flicker method possesses many desirable characteristics, yet at present it can hardly be accepted as yielding 'true' measurements of brightness unless the difference in the results, obtained by this method and by the direct comparison method, be ignored. Where color differences are large — just where such a method as the flicker method is most desired — the results by the two methods vary most widely.

56. *Luminosity Curve of the Eye.* — Ives found that the spectral luminosity curve obtained with the direct comparison photometer by the 'cascade' method (involving small steps of slight hue difference) agrees at high illumination for a small field with the curve obtained by the flicker photometer. He also found that the latter method fulfilled certain fundamental axioms, namely, that the sum of several individual brightnesses of different hue must equal the brightness of the whole and that if each of two brightnesses of different hue equal a third brightness, they must be equal to each other, while the direct com-

parison method did not. While these experiments point with favor to the flicker method, it is true that a method can fulfill these requirements and yet not yield measurements of 'true' brightness. However, it appears at the present time that the balance of experimental data is strongly in favor of the flicker photometer. For this reason the relation between radiation of various wave-lengths and their physiologic effect in producing luminous sensation as

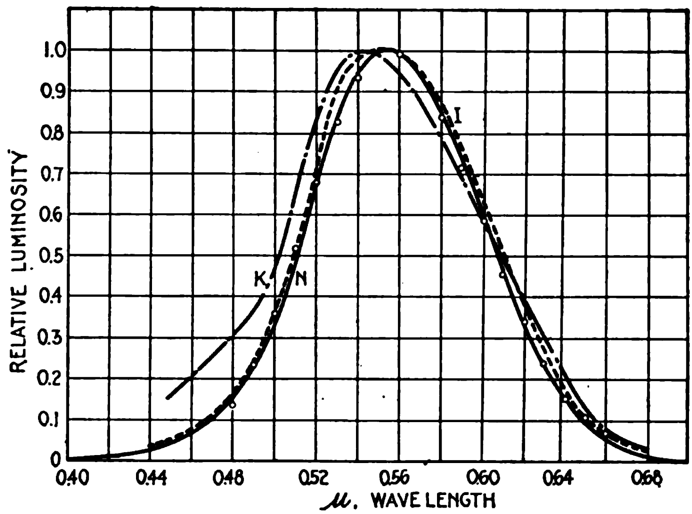

Fig. 93.—Visibility data. (See Table XVI.)

obtained with the flicker photometer is of considerable interest. Ives [24] determined the luminosity curves of 18 observers which he has published in comparison with the mean curve. Later he determined the luminosity curves for 25 more observers, which mean, he states, agrees well with that of the previous eighteen. Nutting [25] has recently obtained such data with 21 observers. The apparatuses used by both Nutting and Ives were practically the same as shown in Fig. 51, the source *W* being eliminated.

The data as presented by Nutting are shown in Fig. 93 and Table XVI compared with Köenig's[26] origi-

TABLE XVI

The Visibility of Radiation (See # 92)

Wave length (μ)	Nutting mean visibility	Ives mean	Köenig mean	Computed from Nutting's formula
0.400	0.002	.....	.....	.....
0.410	0.003	.....	.....	.....
0.420	0.003	.....	.....	.....
0.430	0.012	.....	.....	.....
0.440	0.023	0.029 [1]	.....	.....
0.450	0.038	0.047 [1]	0.158	.....
0.460	0.066	0.073 [1]	0.201	.....
0.470	0.105	0.107 [1]	0.250	.....
0.480	0.157	0.154	0.302	0.135
0.490	0.227	0.235	0.370	0.232
0.500	0.330	0.363	0.476	0.358
0.510	0.477	0.596	0.670	0.514
0.520	0.671	0.794	0.830	0.675
0.530	0.835	0.912	0.950	0.824
0.540	0.944	0.977	0.996	0.933
0.550	0.995	1.000	0.990	0.994
0.560	0.993	0.990	0.945	0.993
0.570	0.944	0.948	0.875	0.939
0.580	0.851	0.875	0.780	0.839
0.590	0.735	0.763	0.680	0.717
0.600	0.605	0.635	0.585	0.585
0.610	0.468	0.509	0.492	0.456
0.620	0.342	0.387	0.396	0.343
0.630	0.247	0.272	0.300	0.235
0.640	0.151	0.175	0.210	0.158
0.650	0.094	0.104	0.128	0.108
0.660	0.051	0.068 [1]	0.070	0.072
0.670	0.028	0.044 [1]	0.032	.....
0.680	0.012	0.026 [1]	.....	.....
0.690	0.007	.....	.....	.....
0.700	0.002	.....	.....	.....

[1] Extrapolated.

nal data which was obtained by the direct comparison method. Nutting has extended the observations well into the red and violet regions of the spectrum by

using sources emitting line spectra. Köenig's data are shown in curve *K*, Ives' data in curve *I*, and Nutting's data in curve *N*. Nutting developed a formula of the form $V = V_m R^a e^{a(1-R)}$ from which the values given in Table XVI and represented in Fig. 91 by the circles have been computed. V_m in the formula represents the maximum light-producing effect, $R = \frac{\lambda_{max}}{\lambda}$, $a = 181$, and V the visibility or relative light-producing value of energy of any wave-length, λ. The maximum sensibility is at $\lambda_{max} = 0.555\mu$. The computed values are found to coincide practically with Nutting's mean luminosity curve between wave-lengths, 0.48μ and 0.65μ.

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CHAPTER X

COLOR PHOTOGRAPHY

57. At the present time no processes of color photography have been developed which employ the simple principle of fixing the colors of Nature directly upon the photographic plate by chemical means. O. Wiener[1] discusses the use of body colors which would assume the colors corresponding to the rays of light by chemical modification. Carey Lea[2] obtained a form of silver photochloride which assumed different colors on exposure to various rays, but no means was found for fixing them. Most of the commercial methods employ colored media which reproduce colors by one of the common methods of color-mixture. In the first place the emulsion must be sensitive to all visible rays, and preferably the plate should be sensitive to light rays, in closely the same manner as the eye. There are no commercial plates endowed with the latter characteristic, so panchromatic plates are usually used with an approximate color filter. Ray filters of the accuracy approaching that illustrated in Fig. 91 are rare, but for accurately photographing colored objects in their true values of light and shade, carefully made filters must be used with panchromatic plates, because the latter differ greatly in spectral sensibility from the eye (Fig. 90). In other words, a plate must be rendered of the same relative sensibility to the various visible rays as the eye by the use of sensitizing dyes and ray filters.

Fortunately ordinary photography does not require such a high degree of accuracy.

About a century ago Seebeck discovered that silver chloride becomes tinted by exposure to light with an accompanying chemical action. It is also possible by properly selecting luminescent salts to produce a series of tints after exposure which are very effective. Such colors cannot be fixed, and therefore are of little practical interest. The development of color photography has been confined largely to two methods. In one the phenomenon of interference of light waves is utilized to reproduce colors directly, while the other method is based upon the principles of color-mixture — both additive and subtractive (#18, #19). In the latter method artificial color-screens are used. Sometimes these are of minute size, as will be shown later.

58. *Lippmann Process.* — The method employing interference of light waves is originally due to Becquerel,[3] but Lippmann's name is usually associated with the process, owing to the improvements which he devised after extensive investigation.[4] Zenker [5] in 1868 explained the colors sometimes exhibited by spectrograms made on silver chloride plates as due to the interference of light waves reflected from layers of metallic silver which are originally produced by stationary light waves. Among those who have investigated the process are Wiener,[6] Neuhaus,[7] Valenta,[8] Lehmann,[9] and Ives.[10]

In the Lippmann process the sensitive film is backed by a film of clean mercury which acts as a reflector. As light which has passed through the thin film strikes the layer of mercury it is reflected back on its path, and owing to the disappearance of energy at certain points through interference, the

silver compound is acted upon only in layers — at the antinodes. The phenomenon is diagrammatically shown in Fig. 94. The silver compound, instead of being acted upon throughout the thickness of the film, is largely reduced in thin laminæ the distance between which is one-half a wave-length of the light producing them. Especially fine-grain plates must be used in order to produce the very minute structure. The emulsion must be sensitive to all colors which are so made by the use of certain sensitizers. This discovery is due to H. W. Vogel, in 1873, who found that silver bromide by treatment with certain sensitizing dyes, such as eosine and cyanine, was rendered sensitive to rays of longer wave-length than when untreated.

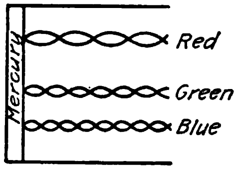

Fig. 94. — Illustrating the standing waves produced in the Lippmann process.

If the plate after exposure in the Lippmann process be developed and illuminated by white light, from various parts of the film only colored light escapes to the eye and a photograph in colors is seen. It is easy to account for the reproduction of pure spectral colors, but the general theory has been the subject of much discussion too extensive to dwell upon here.

59. *Wood Diffraction Process.* — This method, invented by R. W. Wood in 1899, depends upon the phenomenon of interference, though in a different manner. It depends upon the principle that all colors may be matched in hue by mixtures of three primary colors, red, green, and blue, each consisting of a narrow band of the visible spectrum. These spectral primaries lie near the regions of the spectrum corresponding respectively to 0.65μ, 0.52μ, and 0.45μ. This process utilizes diffraction gratings for the pro-

duction of the primary colors. If a point source of light or an illuminated slit be viewed through a diffraction grating (#9), not only will an image of the source be seen, but displaced on either side a series of spectra will be seen. The displacement of the spectra from the line joining the eye and light source will depend upon the number of lines per inch in the grating; the fewer lines per inch the less is the displacement. The primary spectral colors are produced as shown in Fig. 95. If a source of light *S*, a lens *L*, and a grating *G*, be arranged as shown, an image of the source will be seen on a screen at *I*. With a

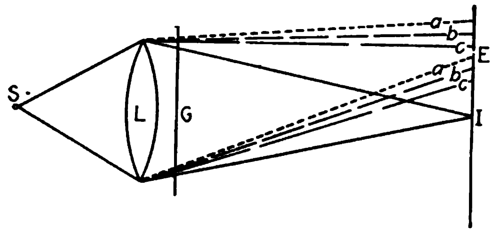

Fig. 95.—Illustrating the Wood diffraction process.

fine grating a spectrum of the source will be seen on the screen extending between *aa*. With a coarse grating a spectrum of the source will be formed between *cc* and a medium grating will produce a spectrum at *bb*. If the three gratings have different rulings, the eye at *E* will see the lens face illuminated by a monochromatic color depending upon the grating interposed at *G*. If all three spectra be produced simultaneously in proper intensities, the eye at *E* would see the lens face illuminated by white light providing gratings of proper rulings are chosen. Such a scheme was used by Wood for viewing the photographs. The latter, which appear colorless, really consist of images of the object made on plates of bichromated gelatine through three properly chosen

gratings. In making the photographs one of the gratings was placed in contact with the bichromated gelatine film and the image of the object was projected upon the sensitive film through the grating. This grating was then replaced by another and the procedure repeated. It was then repeated a third time with the remaining grating, but usually with another sensitive plate. On superposing the two exposed plates and viewing by a proper combination of lens and light source the picture was seen in colors. Copies can be made by contact printing. It was found, however, that while satisfactory pictures could be made there was no certainty about obtaining them. This was later found to be due to superposing the three grating exposures. Ives[11] improved the process by printing the grating pictures through a very coarse grating placed at right angles to the lines of the three gratings. The coarse grating had opaque lines twice the width of the transparent strips. After making an exposure through one of the gratings the coarse auxiliary grating was moved in a direction perpendicular to its lines a distance equal to the width of one of its open slits and an exposure was made through the second grating. This procedure was repeated for the third grating. The lines of the coarse auxiliary grating were as in the so-called Joly process to be discussed later, so narrow as to be just unresolved by the eye — about 200 to the inch. This process yielded satisfactory results. Ives further simplified the process by making one grating answer the purpose of the original three by using the finest grating — 3600 lines per inch — and rotating it in its plane respectively 21.5 and 42 degrees for the other two exposures. Thorp, unknown to Ives, had previously suggested the use of one grating for a

similar purpose. When using three gratings, one with 2400 lines per inch furnished the red component, one with 3000 the green, and one with 3600 the blue. F. E. Ives worked out a viewing apparatus involving important improvements over Wood's original scheme.

60. *Color Filter Processes.* — If an object be separately photographed on three panchromatic plates respectively through properly chosen red, green, and blue filters (which collectively transmit all visible rays) and these three photographs be separately projected upon a white screen by means of three projection lanterns equipped with the foregoing colored filters, three separate 'monochromatic' photographs will be seen. If, however, the three colored images — red, green, and blue — be superposed in exact coincidence, a picture in natural colors will be seen. The principle is that of adding colors as shown in Fig. 21. F. E. Ives, who was a pioneer in this field, developed an apparatus for viewing the three-colored photographs simultaneously and also the so-called chromoscope for tri-color projection of photographs made in this manner. Charles Cros independently developed a similar method. In 1868 Louis Ducos du Hauron described a process for three-color photography (since known as the Joly process) which involved the ruling of red, green, and blue lines of transparent dyes on a transparent screen. The lines were too fine to be distinguished by the eye. The procedure involves the juxtapositional method of color-mixture, a principle long used in the textile industry and in painting. If a photograph be made through such a screen and a positive made therefrom, the latter will appear in colors when viewed through the original screen when properly superposed. The screen is diagrammatically shown largely mag-

nified in Fig. 96. (In Figs. 96, 97, and 98 red, green, and blue are represented respectively by the horizontal lines and the diagonal lines running in directions perpendicular to each other.) There have been numerous variations of this scheme commercialized. The Paget screen is illustrated in Fig. 97. An interesting development is the Lumière process. Minute grains of dyed starch are used in a thin layer over a sensitive emulsion. Three batches of transparent starch grains are dyed respectively orange-red, green,

du Hauron

FIG. 96

Paget

FIG. 97

Lumière

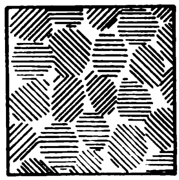

FIG. 98.

Green Red Blue

Illustrating three processes of color photography.

and blue. These are mixed in such proportions as to give a mixture of neutral color and are spread on the plate in a single layer. A portion of the plate greatly magnified is shown diagrammatically in Fig. 98. The light passes through the minute color filters of dyed starch before striking the plate. The plate is developed in the ordinary manner, and by chemical means the negative is converted into a positive. The reversal may take place in a bath of potassium permanganate acidified with sulphuric acid and is later developed again in the same developer as used in the first development. After drying, the plate is varnished and the color photograph is ready for

viewing. The process is a very ingenious one and reproduces natural colors quite satisfactorily. A deficiency of the process of no great importance in most work is shown in Fig. 99. It is also of interest in showing the inability of the eye to analyze colors. The approximate transmission of the three dyes are diagrammatically shown. It is evident on photographing the solar spectrum that the dyes used are somewhat too monochromatic, because the colored spectrogram which consists of red, green, and blue bands shows gaps between the blue and green, and also between the green and red where little color is visible. For instance in a spectrogram of the mercury spectrum the yellow lines at 0.578μ appear an orange-red. This defect is evident in a greater or less degree in the foregoing processes, depending upon the spectral character of the colored dyes. However, owing to the fact that colors ordinarily encountered are far from monochromatic, this deficiency is unimportant and practically negligible in ordinary color photography. This defect is encountered with regret when one desires to reproduce spectra for demonstration purposes. For the latter purpose the methods employing the three colored transparencies about to be described are satisfactory. The foregoing methods are based upon the additive and juxtapositional processes of color-mixture. The processes using the minute color filters shown in Figs. 96, 97, and 98 have a disadvantage in loss of light. For instance, if the process be analyzed it will be seen that a red object will be recorded upon the photo-

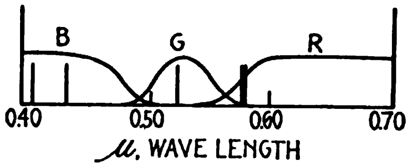

Fig. 99.—Illustrating the limitations of certain processes of color photography.

graph in general in the proportion of one red patch to two black patches. That is, no red light will be transmitted by the minute blue and green filters, so in the final photograph these will appear as black spots. This is a decided disadvantage in the making of colored lantern slides for projection unless an exceedingly powerful arc lamp is available. A number of processes employing subtractive method (#18) have been developed. Sanger Shepherd developed a method wherein three differently colored films such as are indicated in Fig. 20 are superposed in a single transparency. F. E. Ives was also a pioneer in this field. The process is identical in principle with the tri-color printing process in use at the present time, with the exception that in the latter case a black-white record is sometimes used with the three color records. Three negatives are made respectively through red, green, and blue filters from which positives are made on special thin transparent films of celluloid coated with gelatine sensitized by immersion in a solution of bichromate of potash. The transparencies are each dyed a color complementary to that of the taking filter, the red record being colored blue-green (cyan-blue); the green record, purple (magenta); and the blue record, yellow. These transparencies are free from opaque silver deposit, the gradation being from a maximal transparency to the deepest color of the dye on each film. On superposing them the natural colors are produced by the subtractive method, as will be readily understood from an inspection of Fig. 20. F. E. Ives devised a method after this principle whereby the three plates were exposed simultaneously with one lens. Shepherd first employed a repeating plate holder so that the three plates were successively exposed through

the proper filters. A few years ago a process of producing moving pictures in colors known as Kinemacolor was launched. In order to simplify the matter only two colors are used, namely a blue-green and an orange-red. The different colored images are alternately thrown on the screen at the usual rate. It is obvious that the use of three colors would render the problem exceedingly complex. Such a two-color method cannot reproduce all colors with fidelity, but the results are quite satisfactory considering the simplification that is obtained. Recently another scheme, employing only two colors, has been developed, known as the Kodachrome process. By means of a repeating back two plates are successively exposed through red and green filters respectively. These are developed in the ordinary manner and after being washed they are bleached and fixed, at this stage appearing transparent. They are next given a final washing in a weak aqueous solution of ammonia and dried. Finally the plates are dyed, the one made through the red filter being dyed a bluish-green and the one made through the green filter an orange-red.

In general the processes employing dyed transparencies superposed yield more brilliant color records, but are obviously more dependent upon the skill of the photographer. In much work the processes employing the juxtapositional method of color-mixture are more satisfactory owing to the simplicity, notwithstanding the less brilliant results. Of the latter methods those employing the ruled screens are somewhat more flexible; however, the adjustment of the viewing screens requires some patience.

It is thus seen that at the present time the problem of color photography has been solved by rather

indirect methods involving color-mixture. Most of the methods will be completely understood on referring to Chapter III.

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CHAPTER XI

COLOR IN LIGHTING

61. Lighting is of great importance, because it is essential to our most important and educative sense — vision — and color is intimately associated with lighting and vision. Color in lighting is rapidly growing in interest in the science and art of illumination. The recent increase in the luminous efficiency of light sources and the rapid strides in the development of the art of lighting are largely responsible for the growing interest in color and quality of light. Much is yet to be learned regarding the physiological and psychological effects of color, and the laws for its proper use are hazy and not well understood. However, equipped with a full knowledge of the physics of color, an æsthetic taste and a comprehensive view of what is known and unknown regarding the physiological and psychological influence of color, a person is capable of utilizing many of the possibilities of color in lighting. The illuminant plays a very important part in the appearance of colors, as has been seen in Chapter VII. The spectral character of the illuminant influences the hue and relative brightness of colors, and the intensity influences the hue and apparent saturation. At low intensities the hue shifts toward the shorter wave-lengths and at high intensities there is an apparent decrease of saturation. The distribution of the light affects the appearance of colors, owing to the character of these surfaces. All of these factors are of importance in

considering the proper illuminant for accurate color work in the dye-rooms of textile and paper mills, in the mixing of pigments for color printing and for painting, for the matching of colors, and in many other places. The spectral character of illuminants is of importance (#37) in the discrimination of fine detail, for it has been seen that monochromatic light is superior in defining power to light of any other spectral character.

There are many important problems as yet unsolved which involve color in its application to lighting. There are practically no data on the influence of color on eye fatigue, although it is known that colors are of influence psychologically. There is a prevalent idea that the kerosene lamp is 'easy on the eyes,' owing to its yellowish color. However, the low intrinsic brightness of the kerosene flame as compared with more modern illuminants is a fact worthy of consideration. When it is further noted that there is no general objection to daylight on account of its color — and it is far whiter or more bluish than ordinary illuminants — it must be admitted that the virtue of the kerosene lamp based upon its color is on a rather shaky foundation. It is likely that the eye having evolved under daylight is better adapted to it than to any other illuminant and that the nearer an artificial illuminant approaches daylight in spectral character the more likely is it to be satisfactory physiologically. Misuse of common illuminants is perhaps responsible for eye-fatigue to a greater extent than any spectral characteristics. One cannot look directly at the sun and state conscientiously that daylight is ideal. It has been found that visual acuity is better in monochromatic light than in daylight (#37), and it may appear from this

that daylight is not ideal. However, these experiments were carried out at ordinary intensities considered satisfactory in artificial lighting, and daylight intensities are ordinarily very much greater, which means that, for the discrimination of ordinary details, the intensity is many times the minimal amount required, so that the limit of defining power is seldom reached. For years many have held that the eyes are less fatigued when reading from yellow paper than from white paper. In a biography of Joaquin Miller we read that 'he wrote on yellow paper with a pencil because white paper hurt his eyes.' Babbage many years ago strongly advocated the use of yellowish paper in reference books, such as logarithm tables, where the eyes are severely taxed. Javel later advocated the same procedure, claiming that eye-strain was decreased, owing to a decrease in contrast. Many are of the same opinion although, as already stated, quantitative data relating directly to the problem are lacking. After reading from white paper the eyes seem to welcome a change to yellow paper, but this may be due to a decrease in contrast, owing to a lower reflection coefficient of the yellow paper than that of the white paper. However, measurements show only a slight difference in the brightness of pale yellow copy paper as compared with white, especially under ordinary artificial light. There is no doubt that a yellow or yellow-green light of less extended spectral character than daylight or ordinary artificial light is of superior defining power, due to the reduction of the effects of chromatic aberration in the eye. This fact may partly account for the contention that yellow paper is 'easier on the eyes.' It is difficult to focus blue light at a normal reading distance, and impossible to do this at the same time

keeping the most luminous rays in focus, therefore, the elimination of the blue rays by means of yellow paper may actually increase the definition. However, reading does not ordinarily involve the discrimination of fine detail, but instead the recognition of groups of characters. Furthermore, the eye is found to progress across a page in a series of jumps, being stationary only a few times per line. It has been found that there is practically no difference in visual acuity when the detail is viewed against a white ground and a ground consisting of yellow copy paper when both receive the same intensity of illumination, that is the same density of light flux.

Colored surroundings, such as foliage, brick walls, the wall coverings of the room, etc., alter the spectral character of light before it arrives at the useful plane. Such effects must be considered in any lighting problem requiring a light of a certain spectral quality and are also of importance from the æsthetic viewpoint. Many uses of illuminants of different color and colored media are found in the problems of lighting.

62. *The Production of Artificial Daylight.* — The arts having developed largely under daylight illumination, the daylight appearance of colors is naturally considered as standard. With the production of artificial light man became less dependent upon daylight; nevertheless, owing to the impracticability and perhaps impossibility of a dual criterion of color, there has always been a demand for artificial daylight. The efforts in the production of artificial light have been directed toward the production of light of daylight spectral quality. The principal reason, no doubt, is that such a procedure in our most important method of producing light (by high temperature radiation) at the present time tends toward an ever-increasing

luminous efficiency. Nevertheless each increment in the steady approach toward daylight has been loudly acclaimed by reason of the better 'color-value' of the illuminant. However, there is a method which has been applied whereby light of a daylight character can be obtained by excluding from an illuminant containing all the rays found in daylight, those portions which are present in excessive amounts. Such a subtractive method is wasteful of light, but is made practicable by the recent increase in the luminous efficiency of illuminants. However, it is well to remember that efficiency in lighting as in any other case is 'the ratio of satisfactoriness to cost and not the reciprocal of the cost.'

In order to produce artificial daylight it is necessary to determine the spectral character of natural daylight. First it is well to distinguish between sunlight and skylight. The latter is scattered sunlight, but owing to the relatively greater scattering of the rays of short wave-length (#13) skylight is more bluish in color than sunlight. Daylight varies tremendously with time and place, although north blue skylight and clear noon sunlight, when unaltered by reflection from immediate surroundings, are fairly constant in color. However, the modification due to selective absorption of the particles in the atmosphere and selective reflection from foliage, buildings, etc., make daylight rather indefinite in spectral character. E. L. Nichols [1] has published interesting accounts of his investigations on the spectral character of daylight under different conditions of weather, cloudiness, location, and time of day. He found among other things unmistakable evidence of the coloring added to daylight by reflection from green foliage by noting the characteristic absorption spec-

trum of chlorophyl (a substance in green foliage) present in observations made on land in the summer time. This effect was absent on the sea. Koettgen,[2] Nichols and Franklin,[3] Crova,[4] Vogel,[5] Ives,[6] and others have studied the spectral character of daylight. The data on noon sunlight and skylight plotted in Fig. 5 is a weighed mean of the results of the foregoing investigators as presented by Ives. The distribution of energy in the visible spectrum of clear noon sunlight as it reaches the earth corresponds closely to that of a black body at 5000 deg. absolute (*C*).

A number of investigators, including Dufton and Gardner,[7] Mees,[8] Pirani, Ives,[9] Hussey,[10] and Luckiesh[11] have devised colored screens for producing artificial daylight by altering the light from an artificial source emitting a continuous spectrum. In order to demonstrate the procedure and illustrate the advantage of first choosing a light as close to daylight as possible, the production of daylight screens for two tungsten lamps of different luminous efficiencies as considered by Luckiesh and Cady [11] will be presented.

The visible spectrum of the light from a tungsten lamp being continuous, it has all the rays present that are found in daylight. The difference in their spectral characters is due to the difference in the relative amounts of the various rays present. First let us consider the production of light of noon sunlight quality from a vacuum tungsten incandescent lamp operating at 7.9 lumens per watt (1.25 w.p.m.h.c.). It is found sufficiently accurate to consider no rays of shorter wave-length than 0.42μ. An ideal screen for altering the tungsten light to a noon sunlight quality will therefore transmit all the rays of wave-length 0.42μ. It will partially absorb rays of longer wave-

length in increasing proportions from 0.42μ toward the long-wave end of the spectrum. The reduction of the intensity of the rays of various wave-lengths is readily computed from the ratios of the amounts of these rays present in noon sunlight to the amounts of the corresponding rays present in the tungsten light under consideration. The resultant transmission curve of a colored screen for thus altering the

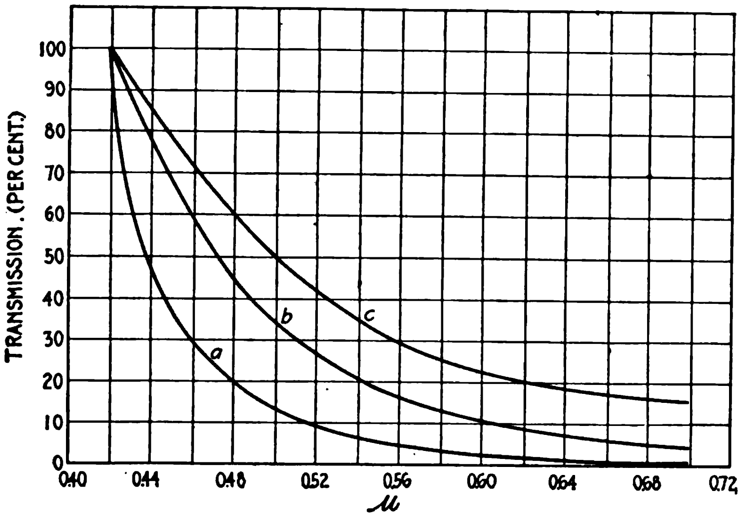

Fig. 100.—Ideal transmission screens for producing artificial daylight.

tungsten light (7.9 lumens per watt) to noon sunlight quality is shown in *b*, Fig. 100. The ideal transmission curve of a colored screen for producing artificial noon sunlight by means of a nitrogen-filled tungsten lamp operating at 22 lumens per watt (0.5 w.p.m.h.c.) is shown in *c*. In order to produce artificial north skylight it is seen in Fig. 5 that the visible rays of long wave-length must be reduced by relatively greater amounts than in producing artificial noon sunlight. The ideal transmission curve for producing artificial north skylight by means of the tungsten

lamp operating at 7.9 lumens per watt is shown in *a*. The ideal transmission curve for producing artificial north skylight with the gas-filled tungsten lamp operating at 22 lumens per watt coincides closely with *b*. That is, a screen which produces artificial noon sunlight with the oldef type of tungsten lamp operating at 7.9 lumens per watt will produce artificial skylight when used with the gas-filled tungsten lamp operat-

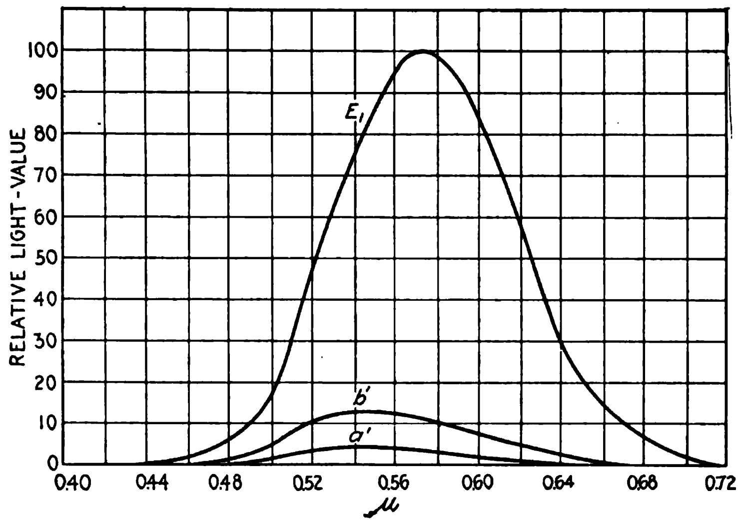

Fig. 101.—Showing the loss of light when using the ideal artificial-daylight screens with the tungsten lamp operating at 7.9 lumens per watt.

ing at 22 lumens per watt. This fact has been taken advantage of by the author in developing daylight units. These curves show the increased daylight efficiency of the tungsten lamps operating at higher luminous efficiencies. This is further illustrated in Figs. 101 and 102. In the former E_1 represents the luminosity curve of the eye for light from a tungsten lamp operating at 7.9 lumens per watt, that is, the relative light values of the rays of various wavelengths. This curve may be found directly or by mul-

tiplying the mean luminosity curve of the eye (Fig. 93) for equal amounts of energy of all wave-lengths by the amounts of energy of various wave-lengths in the spectrum of the light under consideration. In this case it is the 7.9 lumens per watt tungsten lamp whose spectral energy distribution is found in Fig. 5. On multiplying curve E_1 by the transmission values of curve a, Fig. 100, curve a' is obtained. The

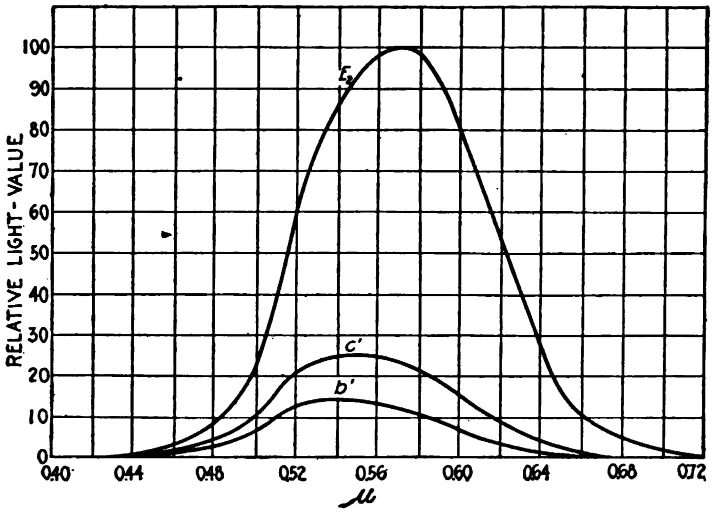

Fig. 102.—Showing the loss of light when using the ideal artificial-daylight screens with the tungsten lamp operating at 22 lumens per watt.

areas under curve E_1 and a' are proportional to total luminous sensations, and the ratio of the area of a' to that of E_1 represents the skylight efficiency of the 7.9 lumens per watt tungsten lamp as based upon the foregoing computations. The reduction in luminous intensity when screen b is used with the source under consideration is found on comparing b' with E_1, in Fig. 101, and the ratio of the areas represents the sunlight efficiency of the 7.9 lumens per watt tungsten lamp. The corresponding data for screens

b and c used with the 22 lumens per watt gas-filled tungsten lamp are shown in Fig. 102, where E_2 represents the luminosity curve of the eye for this tungsten light. Screen b produces skylight and reduces the luminous intensity an amount represented by the difference between the area of b' and E_2 in Fig. 102. Screen c produces noon sunlight with an efficiency represented by the ratio of the area of c' to that of E_2.

The daylight efficiencies for the two lamps considered in the foregoing were found by determining the relative areas. For the 7.9 lumens per watt tungsten lamp (vacuum type) the noon sunlight efficiency is 14% and the skylight efficiency 4%. However, for the 22 lumens per watt tungsten lamp (nitrogen-filled type) the corresponding values are considerably higher, being 25% and 13% respectively. It has been found in actual practise that the consideration of 0.42μ as the starting point for the computations just described conduces to a higher accuracy than necessary in most cases, therefore beginning with a screen of 100% transmission at 0.45μ the daylight efficiencies are very considerably increased. Under these circumstances for the 7.9 lumens per watt lamp the sunlight and skylight efficiencies are respectively 18% and 9% and for the 22 lumens per watt lamp 33% and 19%.

It is thus seen that very accurate artificial noon sunlight can be obtained with an ideal colored transmission screen with the 22 lumens per watt lamp at an efficiency of 25% or at 5.5 lumens per watt. This is a higher efficiency than that of the ordinary carbon incandescent lamp operating normally at the present time. Artificial daylight sufficiently accurate for nearly all purposes can be made at a much higher efficiency. The author has developed bulbs for the

high efficiency tungsten lamp that produce artificial daylight satisfactory for general illuminating purposes. Thus the advent of the high efficiency lamps has made artificial daylight available, and now that it is practicable it is surprising how many places are found for it. Besides in the general field of store lighting, artificial daylight is useful for mixing pigments, matching artificial teeth and buttons, cigar sorting, medical examination of manifestations of skin diseases, green houses where botany classes study at night, observations of chemical reactions, and for many other operations.

The production of colored media for the above purpose requires spectrophotometric apparatus. Mistakes have been made by using colorimeters or by using merely the eye to judge the color. As has already been seen, the eye is undependable for such purposes, because it is not an analytical instrument for the examination of color. Two lights may appear white to the eye, yet differ considerably in spectral character. For instance, ultramarine blue of a proper density will so alter tungsten light by transmission that a white paper will appear quite the same as under daylight, yet colored objects will appear greatly different. Such a screen is very useful for demonstration purposes. The distribution of energy in the visible spectrum of a white light produced with an ultramarine filter screening a tungsten lamp operating at 10 lumens per watt as compared with that of noon sunlight, *S*, is shown in *U*, Fig. 103. This unit was once seriously proposed as a 'daylight lamp,' but was short-lived for the reason shown. Another white light is shown in curve *C*, which is produced by the addition of red and blue-green light. It is similar to the ultramarine white light, yet more ex-

treme. These three illuminants are called 'white,' because a white object appears the same under all of them; however, a colored object does not. A quartz mercury arc will cause a white paper to appear nearly white, yet its spectral composition is known to consist chiefly of four lines in the visible region.

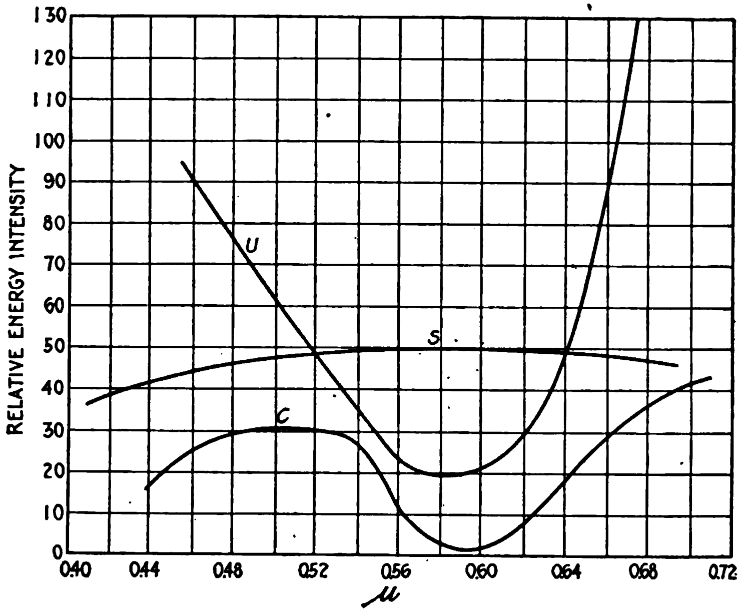

Fig. 103.—Showing the spectral analyses of two subjective white lights compared with the spectral analysis of noon sunlight.

These examples illustrate the importance of spectrophotometric measurements in such problems.

Another method of producing daylight is to add to a continuous-spectrum illuminant the correct amounts of certain rays which are not present in sufficient amounts. To most artificial illuminants of this character violet, blue, and blue-green rays must be added. To illustrate the procedure the two tungsten lamps considered previously will be used. In Fig. 104 curve *S* represents the spectral distribution of energy in

noon sunlight. Curves *A* and *B* represent respectively the spectral distributions of energy for the two tungsten lamps operating at 7.9 and 22 lumens per watt. These three curves are plotted with their energy values equal at 0.70μ, a point near the practical limit of visibility for long-wave energy. By subtracting the ordinates of *A* and *B* respectively

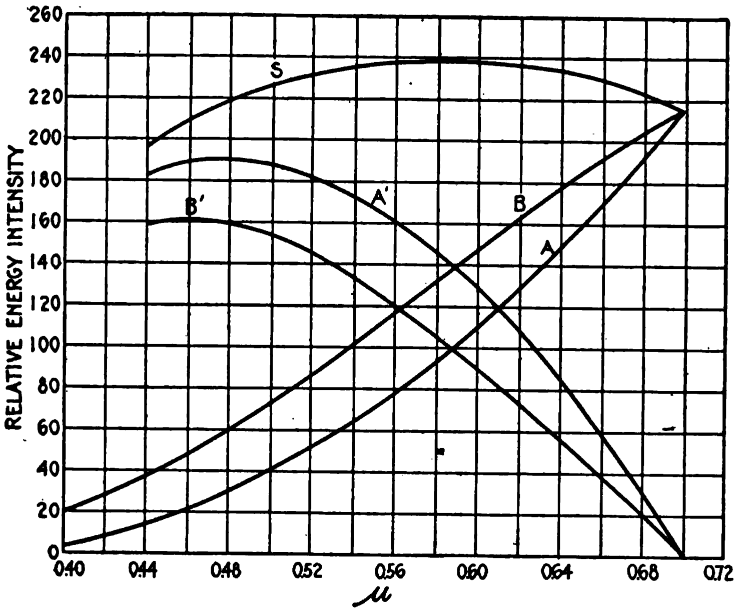

Fig. 104.—Showing the additive method of producing artificial daylight.

from the ordinates of *S* and plotting the remainders, curves *A'* and *B'* are obtained. These curves are complementary to *A* and *B* respectively; that is, the light produced by *A* when added to the light produced by *A'* gives the same amount of light and of exactly the same spectral character as the light produced by *S*, which is assumed to be white light. By multiplying the ordinates of *S*, *A*, and *B* by the light values of energy of corresponding wave-lengths the curves in Fig. 105 are obtained. For example, *S* is

the luminosity curve of the eye for noon sunlight. On integrating these curves the relative areas under *S*, *B*, and *A* are respectively 100, 50, 33. Thus it is seen that equal amounts of light from a nitrogen-filled tungsten lamp operating at 22 lumens per watt and light of such a spectral character as *B′*, Fig. 104, will produce artificial noon sunlight. However one part

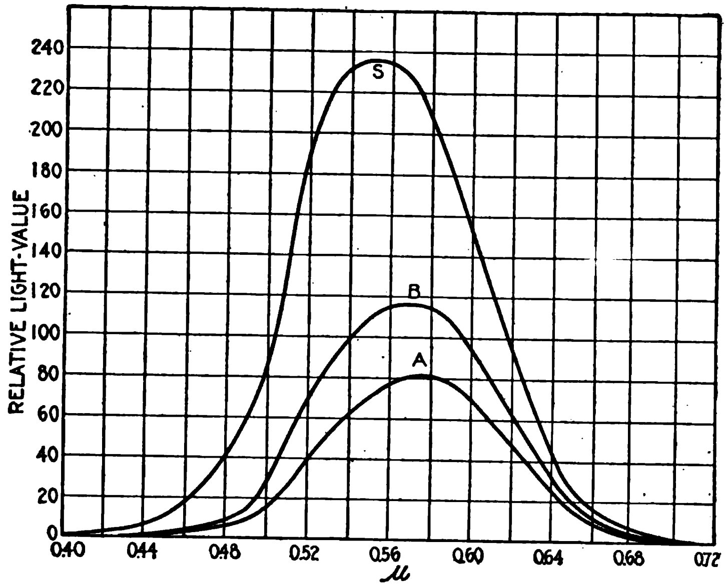

Fig. 105.—Showing the relative amounts of light of the character of A and B (Fig. 104) necessary to produce artificial daylight by addition.

of light from a vacuum tungsten lamp operating at 7.9 lumens per watt must be added to two parts of light of the character of *A′*, Fig. 104, to produce artificial noon sunlight. These data have proved of value in the use of colored lamps with clear lamps for the lighting of paintings and other decorative colored objects.

In Table VII the 'per cent white' values obtained by L. A. Jones [12] for various artificial illuminants with a monochromatic colorimeter are presented. His

values show higher daylight efficiencies for the tungsten incandescent lamps than obtained by Luckiesh and Cady.[11] The difference may be partly due to a difference in the standards of white light used and in part to the possible fact that the author's computations were made for artificial daylight of too great accuracy. That is, it is possible that the extremely low luminosity of rays at 0.42μ makes it unnecessary to produce a screen that begins to absorb light at that extremely short visible wave-length. The computations for screens beginning to absorb rays of longer wave-length than 0.45μ more nearly agree with the data obtained by Jones. It is unfortunate that Jones did not rate his tungsten lamps in lumens per watt, which is more definite because the mean horizontal candle-power of a tungsten lamp depends so much upon the manner of mounting the filament. Ives [13] obtained data on the daylight efficiency of illuminants several years ago, but his standard of daylight used at that time does not agree with a standard later arrived at by him by weighing the observations of various investigators, so that his values are not presented here.

63. *Practical Units for Imitating Daylight.* — Luminous efficiency in artificial daylight production is a minor matter in a unit developed for very accurate color-matching. However, there are many cases where light approximating daylight quality is desired for general lighting. Here the wattage is an important consideration, although illuminating engineers and consumers alike must learn that the efficiency of a lighting unit or installation is a measure of how well it fulfills its purpose. This means a broader concept than watts per square foot or effective lumens per watt. If a light source is used for illuminating dress

goods, and blues cannot be distinguished from blacks, and greens as seen in daylight are confused with yellow and brown fabrics under the artificial light, then the efficiency of the lighting installation falls close to zero in these particular cases. As illuminating procedure becomes more refined, and as the efficiency of light production increases, more attention is being given to the importance of quality of light, which is an important factor in many lighting problems. For these reasons glassware for use with tungsten lamps of high efficiency was developed by the author[11] in 1914 which greatly improves the quality of the light, and does so without such an excessive loss of light as would be impractical for purposes of general lighting.

Three phases of daylight have been considered, with the result that three classes of units have been developed. The latest color-matching unit, in which the gas-filled tungsten lamp operating at 22 lumens per watt is used, produces light of a deep blue skylight quality at about 3 lumens per watt. With the multiple lamps of the same type operating at 15 lumens per watt the light corresponds to that of skylight not quite as blue, and the luminous efficiency is about 2 lumens per watt. This unit is used for the purpose of accurate discrimination of color in textile mills, laboratories, color-printing shops, etc. The colored screen is entirely of glass, and as there is no excessive temperature rise in a well-ventilated unit, the glass is permanent and the unit is entirely safe.

The next class of units are intended to imitate clear noon sunlight. This might be considered an average outdoor daylight. There are many cases indoors where the daylight quality is a mixture of sunlight and skylight, and this unit is designed to

produce a satisfactory artificial sunlight at an efficiency of about 7 lumens per watt when multiple tungsten lamps operating at an efficiency of about 16.5 lumens per watt are used. It will be noted that the luminous efficiency at which this artificial sunlight is produced is practically the same as that of the older type of tungsten lamps. Thus sunlight quality is available for general lighting purposes. The applications for such units are to be found in color factories, lithographing plants, wall paper and paint stores, paint shops, cigar factories, art galleries, etc.

Other units have been made by combining this colored element with ornamental glassware, by casing with light-density opal, or by mixing the two intimately. These units are intended for use in general store lighting, where a better quality of light is often desirable than can be obtained from any practical light source available for general store lighting. Any desired step toward sunlight quality can be produced, the magnitude of the step, of course, depending upon the permissible overall luminous efficiency and the color desired. Notwithstanding the blue or white appearance of daylight, when such a quality of light is produced artificially, there is some objection to its use in stores because of the 'cold' appearance, notwithstanding its necessity for the proper appearance of colors. By this means a quality of light better than can be obtained from any unaltered light source for general use is produced at a luminous efficiency sufficiently high to meet with favor. Obviously a quality of light approximately midway between that from the new high efficiency tungsten lamps and sunlight can be obtained at a higher efficiency than that of the older types of tungsten

lamps. Lamps operating at a higher efficiency emit a whiter light, to begin with, thus giving the gas-filled tungsten lamps a dual advantage over those of the older type for the purpose of artificial daylight production. Recently this glass, with a slight modification, has been incorporated into bulbs for the gas-filled tungsten lamps for the purpose of general lighting.

As already stated, any light source having a continuous spectrum, or one nearly so, can be used for the purpose of making artificial daylight. Other desirable characteristics are high luminous efficiency and steadiness of light both as to quality and intensity. The arc lamp early entered the field and has been used considerably, although fluctuations in both the color and intensity have been serious drawbacks. A unit developed by Dufton and Gardner[7] in 1900 appears to be the first practical use made of the colored screen for subtractively imitating daylight. Doubtless there have been many more or less approximate reproductions made by others.

Many are familiar with the beautiful white light of the Moore carbon-dioxide vacuum-tube lamp.[14] No better approximation of average daylight could be desired; however, at present the luminous efficiency of the small units for color-matching purposes is quite low. Certain difficulties have prevented the general adoption of the longer tube, although wherever this unit has been used the quality of the light appears to be very satisfactory.

In 1909 the mercury arc lamp was combined with the tungsten lamp in proper proportions, with the result that a white light was produced. However, this is only an approximate imitation of daylight, the blue lines of the mercury spectrum supplying the

blue rays in which the old tungsten lamp was quite deficient. This combination cannot result in a true daylight as considered spectrally, because the spectrum of the mercury arc consists of only a few lines. The addition of the fluorescent reflector to the mercury vapor lamp greatly improved this illuminant by adding red rays, but this is done partially at the expense of green light. (See Figs. 4, 15, and 16.)

Early in 1911 Ives and Luckiesh,[9] by means of two commercial glasses and an aniline dye, produced a screen for use with the old tungsten lamp operating at 1.25 w.p.m.h.c. for the purpose of producing 'average daylight,' that is, noon sunlight. Later the two glasses were replaced by a single glass, but a correcting aniline dye was still necessary.

In 1912 R. B. Hussey[10] described a screen for use with an intensified arc which produced sunlight quality. This was done by means of pieces from two colored glasses arranged in a checkerboard fashion, with suitable diffusing glasses to mix the light. Owing to the unsteadiness of the arc, spectrophotometric measurements were difficult to make, therefore a colorimeter developed by F. E. Ives was used (#28, Fig. 53). It will be noted that colorimeter measurements are not sufficiently analytical for the purpose of determining the character of the spectrum of a light source. For instance, this instrument will indicate that the quartz mercury arc gives approximately white light, yet this light source emits a line spectrum consisting chiefly, in the visible region, of four spectral lines, as shown in Fig. 4. However, the colorimeter measurements are of interest where the light is known to have an approximately continuous spectrum. This instrument gives readings in terms of red, green, and blue components, which when mixed

produce the same color on a white surface as the illuminant under examination. In Table XVII are

TABLE XVII

Colorimeter Measurements on Units for improving the Spectral Quality of Artificial Light toward Daylight

Source	Colorimeter reading		
	Red	Green	Blue
Average daylight (noonday sunlight)	100	100	100
North blue skylight	78	82	138
Hussey daylight arc lamp	93	111	96
Intensified arc lamp (bare)	147	102	51
Ives and Luckiesh (artificial daylight)	100	93	107
Tungsten 1.25 w. p. m. h. c. (7.9 lumens per watt)	183	96	21
Tungsten 0.65 w. p. m. h. c. (16.4 lumens per watt)	164	102	34
Tungsten 0.50 w. p. m. h. c. (22 lumens per watt)	157	103	40
Tungsten 1.25 w. p. m. h. c. in tinted reflector	145	103	52
Tungsten 0.65 w. p. m. h. c. in tinted reflector	120	102	78
New color matching unit (with 0.65 w. p. m. h. c. tungsten lamp)	80	84	136
Artificial sunlight units (with 0.7 w. p. m. h. c. tungsten lamp)	110	103	87

shown the results obtained with this instrument on Hussey's daylight arc and other data of interest comparable only in a rough manner. The daylight arc examined was a near approach to daylight as far as colorimeter measurements can be trusted, although it shows an excessive greenish component. This could be easily remedied.

Sharp and Millar,[15] in 1912, by means of colored screens and tungsten lamps, also produced a daylight effect. About this time several units, designed to produce artificial daylight, appeared, but no examination of these has been made and no quantitative data are to be found regarding them.

The author [16] has successfully used colored lamps combined with clear tungsten lamps by the additive method, as illustrated in Fig. 104. Blue, green, and

blue-green lamps were used with success for producing daylight effects in combination with clear tungsten lamps. A notable installation was the lighting of the paintings at a large temporary art exhibit in 1913, where more than 400 colored lamps were used. This is perhaps the first large exhibition of paintings where any attempt has been made to produce a daylight appearance by means of artificial light. In order to produce a practical method for obtaining a light of better color value for lighting paintings and other colored objects, many experiments have been made,[11] with the result that, besides the glassware already described, metal reflectors have been used having a tinted surface of such a character as to alter the reflected light to a color complementary to the direct light from the tungsten lamp. Obviously this method results in altering the distribution curve of the reflector, producing in general a less concentrated distribution. This indicates that focusing and intensive reflectors of this character should be used instead of those of extensive type. The results obtained with tinted reflectors show that a very good quality of light is obtained at a loss of about 50 per cent of the original useful light. With coatings of less depth of color the loss of light is less, but the improvement in quality is also less. By changing the shape of the reflector the amount of the altered light can be varied within wide limits. For lighting mural paintings, for instance, the reflectors proved satisfactory. No attempt has been made to reproduce skylight or even sunlight, but a very desirable increase in blue and blue-green rays has been obtained, as shown in Table XVII. The same scheme has been applied to the prismatic glass reflector, a glass coating being applied in this case.

In 1914 Ives and Brady[9] produced a glass for accurate color-matching for use with the Welsbach gas lamp or the tungsten lamp.

Other units have been developed more or less approximating daylight, but some have not fulfilled the claims made for them. There appear to be two fields for artificial daylight units: one where accurate discrimination of colors requires a correct reproduction of skylight, and another field where coarser color work is done, such as in the paint shops and lithographing plants. Light approximating sunlight quality has been found to fill the requirements in the latter field.

The lighting of paintings is treated in Chapter XIII and other colored lighting effects in Chapter XII.

65. *Effects of Colored Surroundings.* — The color value of illuminants has been a subject of considerable discussion and investigation during recent years. Most of the work has been done with colorimeters, which, owing to their limited power of analysis, furnish data which are likewise limited. However, the light that reaches the object is ultimately of greater importance in lighting. This can be greatly altered by selective reflection from surrounding colored objects, but the effect has been a much neglected phase of lighting. G. S. Merrill[17] measured the color value of daylight on the working plane in a room after some of the light had been reflected from the colored surroundings. The interior measurements were made on clear and cloudy days. They showed considerable alteration in the color of outdoor daylight. The author[18] made a study of this factor in a miniature room lighted by means of a tungsten incandescent lamp operating at 7.9 lumens per watt, green, yellow, and white wall papers in various combinations

on the walls and ceiling and direct and indirect lighting systems having been used.

In order to illustrate the possible color change in light due to reflection from a colored surface, it is possible to take an actual case and utilize spectrophotometric data, but for simplicity we will take a hypothetical case. Assume a light source radiating equal amounts of monochromatic red, green, and blue light, and that this source is placed at the center of a hollow sphere the walls of which are covered with a perfectly diffusing green paper. The colorimetric analysis of the illuminant may be expressed as

R	*G*	*B*
100	100	100

The reflection coefficients of this paper for the particular illuminant are assumed to be in per cent,

R	*G*	*B*
25.2	47.2	27.6

The light received by the green paper in the sphere is reflected an infinite number of times. If the walls of the sphere are temporarily assumed to be white and if N is the reflection coefficient of the paper, then the total light falling on the walls will be

$$Q = Q' + NQ' + N^2Q' + N^3Q' + \dots = \frac{Q'}{1 - N} \quad (1)$$

where Q = total light falling on the walls and Q' = direct light from the light source falling on the walls.

The color of a paper is generally determined by measuring the color of the light after it has been reflected once from the paper. It is seen that a total reflection coefficient of $33\frac{1}{3}\%$ has been assumed for the green paper for this particular illuminant. The coefficient of reflection may vary within wide limits

without any change in the color values. Based on the foregoing assumptions the reflection coefficient of this paper for the monochromatic red light is 25.2% of the original 100 units; 47.2% of the total 100 units of green light; 27.6% of the total 100 units of blue light. For this case the total red, green, and blue components in the light incident on the wall paper after an infinite number of reflections will be respectively,

$$Q_R = Q'_R + N_R Q'_R + N_R^2 Q'_R + N_R^3 Q'_R + \dots = \frac{Q'_R}{1 - N_R} \quad (2)$$

$$Q_G = Q'_G + N_G Q'_G + N_G^2 Q'_G + N_G^3 Q'_G + \dots = \frac{Q'_G}{1 - N_G} \quad (3)$$

$$Q_B = Q'_B + N_B Q'_B + N_B^2 Q'_B + N_B^3 Q'_B + \dots = \frac{Q'_B}{1 - N_B} \quad (4)$$

and

$$Q = Q_R + Q_G + Q_B = \text{total light on walls} \quad (5)$$

$$Q' = Q'_R + Q'_G + Q'_B = \text{total direct light on walls} \quad (6)$$

N_R, N_G, N_B are respectively the reflection coefficients for the monochromatic red, green, and blue components of the original illuminant.

$N_R Q'_R$, $N_G Q_G'$, $N_B Q'_B$ are the color values of the wall paper as determined by a tri-color method of colorimetry under the light, Q'.

Computations yield the results given in Table XVIII. On plotting these percentages (shown in the column on the right) in a color triangle, it is shown graphically as indicated in the table that the reflected light rapidly approaches pure green by successive reflection, but of course the intensity rapidly diminishes, as is shown in Fig. 106. It is also instructive to plot the logarithm of the intensity against the number of the reflection which gives a straight line. All three

TABLE XVIII

Computations According to Equations (2), (3), and (4), showing the Changes produced in the Light from a Special Source by Successive Reflections from a Green Paper

The terms in Equations (2), (3) and (4)	Actual values			Percentages		
	R	G	B	R	G	B
Q′	100.00	100.00	100.00	33.3	33.3	33.3
NQ′	25.20	47.20	27.60	25.2	47.2	27.6
N^2Q'	6.35	22.30	7.62	17.5	61.5	21.0
N^3Q'	1.60	10.45	2.10	11.3	73.9	14.8
N^4Q'	0.40	4.93	0.58	6.8	83.4	4.8
N^5Q'	0.10	2.33	0.16	3.8	90.0	6.2
N^6Q'	0.03	1.10	0.04	2.6	94.0	3.4
N^7Q'		0.52	0.01			
N^8Q'		0.25				
N^9Q'		0.12				

components decrease rapidly in intensity with the number of reflections, but the green component does

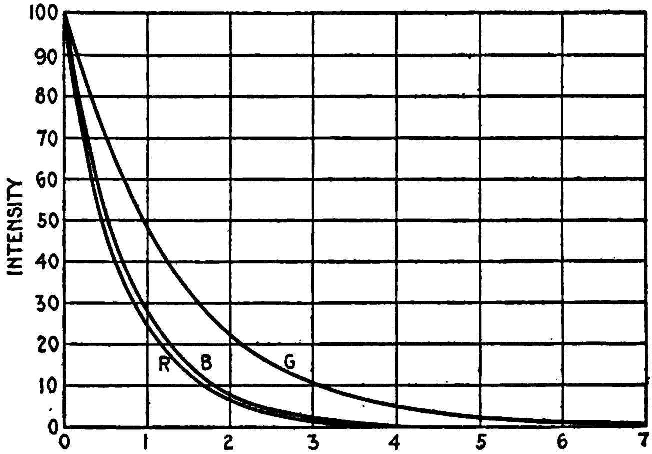

Fig. 106.—Illustrating the effect of multiple selective reflections of light from a green fabric.

not decrease as rapidly as the others. In Fig. 107 are shown the relative values of the three components after various successive reflections. It will be noted

that the color of the light approaches saturated green as the number of reflections is increased. In the original paper various computations were made which relate to conditions of so-called indirect and direct lighting which will not be presented here. However, these indicate, as is shown by actual measurements described below, that the color of the walls and ceiling alter the color of the light in so-called indirect systems very much.

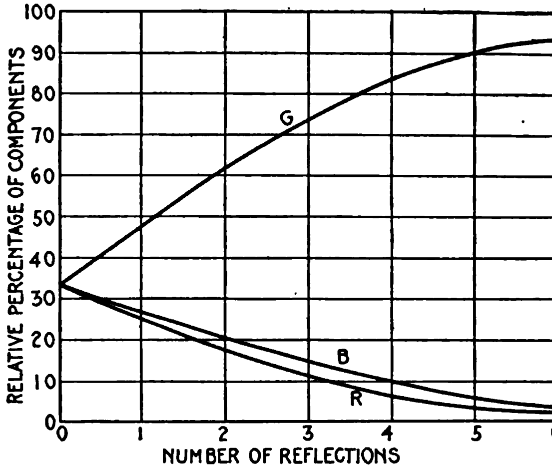

Fig. 107.—Showing the relative proportions of red, green and blue components in the reflected light from a green fabric after various successive reflections.

Actual measurements were made in a miniature room illuminated by tungsten light (7.9 lumens per watt, 1.25 w.p.m.h.c.) of the color of the total light reaching the working plane. The room was four feet square and four feet high and the floor was assumed to be the working plane. The results are presented in Table XIX reduced so that the colorimeter readings for the tungsten lamp used in the investigation equal 100 for each of the three components. This course is considered legitimate inasmuch as only

TABLE XIX

Colorimeter Measurements in a Miniature Room under Various Conditions of Surroundings

	Reduced Colorimeter Readings		
	Red	Green	Blue
1. Tungsten lamp, 1.25 w. p. m. h. c. (7.9 lumens per watt)	100	100	100
2. Tungsten lamp, 0.65 w. p. m. h. c. (17 lumens per watt)	78	96	126
3. Carbon lamp, 3.1 w. p. m. h. c.	116	104	80
4. Carbon lamp, 4.0 w. p. m. h. c.	129	101	70
5. Color of dull yellow wall paper	131	115	54
6. Color of dull green wall paper	104	119	77
(Results with tungsten lamp, 7.9 lumens per watt)			
7. Yellow walls and yellow ceiling, indirect	159	111	30
8. Yellow walls and yellow ceiling, direct	143	107	50
9. Yellow walls and white ceiling, indirect	130	107	63
10. Yellow walls and white ceiling, direct	111	106	83
11. Green walls and green ceiling, indirect	108	139	53
12. Green walls and green ceiling, direct	109	113	78
13. Green walls and yellow ceiling, indirect	145	128	27
14. Green walls and yellow ceiling, direct	119	119	62
15. Green walls and white ceiling, indirect	110	102	88
16. Green walls and white ceiling, direct	106	104	90

the relative magnitudes of the alterations on color are desired. For the sake of comparison the colorimeter readings in the same scale for other incandescent lamps are presented. It is seen that ordinary wall paper of dull yellow color may alter the color of tungsten light so that the useful light is more yellow than the old carbon incandescent lamps. This is a factor too often neglected, and there are cases where lighting experts have striven to improve the color of artificial light by partially correcting glassware, yet this light was permitted to be largely reflected from yellowish walls and ceiling. In stores and other interiors where attempts are made to correct the artificial light the surroundings should be

of a neutral shade or of a slightly bluish tint if this is compatible with the color scheme of decoration. Many possibilities arise where the tinting of light by reflection can be utilized, for, as is seen by the foregoing, the effect can be of considerable magnitude.

65. *Color in Interiors.* — This subject is largely of interest to the decorator, and inasmuch as this book is chiefly confined to the science of color, the æsthetic side of color will not be considered excepting in so far as lighting aids the decorator. Some first principles of interior decoration, however, may not be out of place here. A room has been likened to a painting: the floor representing the foreground; the walls, the middle distance; and the ceiling, the sky. A ceiling may be lowered apparently by treating the walls horizontally, that is by finishing the lower portions of the walls a dark shade and the next section a lighter shade to within two or three feet from the ceiling and permitting the ceiling finish to extend down the walls. Some decorators insist that color has much to do with the apparent size of a room, the lighter tints seemingly enlarging the room.

The color of a room creates its atmosphere. No single color can produce the best effect any more than one note can produce a melody in music. It is the artistic variation in values and tints that satisfies the eye. The principles of masses, spaces, and contrasts, as well as sequences in hue and brightness, play their part in harmonies of color. The law of appropriateness is as important here as in other fields, yet color and brightness are largely matters of individual taste, thus limiting the artist in formulating rules which at best are not thoroughly understood.

North rooms, or those shielded from direct sunlight, are in general more satisfactory when colored

in rose, cream, yellow, buff — the 'warm' colors. Yellowish tints in the window curtains aid in giving the effect of sunshine. On the sunny side, rooms will perhaps be more satisfactory when colored pale blue, gray-green, or shades and tints of other 'cool' colors. In introducing color into the illuminant by means of colored shades or lamps the color scheme of the room should be considered. Apparently many prefer bright red wall coverings, if one may draw conclusions from observations. This again is a matter of personal taste, but extremely pure and bright colors in lighting effects in interiors are to the author like living with a brass band. Many of the lighting effects in pure colors certainly arise from a lack of study of the use and influence of color. If a room is decorated for natural lighting, theoretically it should receive the same artificial lighting both as to direction and spectral character. Yet the change in the lighting — from natural to artificial — may be just the thing to relieve monotony. There are many statements on this subject that cannot be reconciled with the facts. For instance, a person may be satisfied with daylight, living under it from day to day without any other comment than that it is ideal. The same person, however, may object to the increasing 'whiteness' of modern artificial illuminants. He insists that we must go back to the color of the carbon incandescent lamp, or even further to that of the candle flame. Is there a dual standard? Can daylight be satisfactory and the light of the tungsten lamp or Welsbach mantle be too 'white'? As a matter of fact all modern illuminants used in ordinary interiors — the gas and incandescent filament lamps — are in the same class and far yellower than daylight that enters interiors. Color is certainly the keynote of lighting in many

interiors, but let us not base its use upon incorrect premises. If we prefer 'warmer' colors in our artificial illuminants, let us have them, but let us attribute this desire to the proper cause, which may be a love for change in color. Slight tints of rose and yellow may add something pleasing to the complexion, but deep yellow, orange, or red have an obliterating effect upon the flesh tints of the face. They also tend to make colors appear further from their daylight appearance than untinted artificial lights. Using color for color's sake is a legitimate procedure, and in the absence of sufficient physiological and psychological data the use of color must remain, for the present, largely a matter of taste. In lighting it is well to bear in mind the effect of surroundings in coloring the useful light.

Let us take a particular case — the use of amber glass with the tungsten lamp for æsthetic purposes. A combination fixture had an 'indirect' bowl from which hung some direct units with yellow silk shades. The indirect light first passed through an amber glass, then after various reflections from ceilings and walls reached the useful plane. Inasmuch as the majority of living rooms have wall coverings tending toward the yellow, brown, buff, or so-called 'warm' colors, the indirect component is likely to be considerably altered toward yellow in one of these rooms without the use of amber glass. If the wall coverings are of a 'colder' tint why are they satisfactory under daylight and not under the far yellower artificial light? The result obtained with the amber glass would have been obtained without it by the use of a more yellowish wall and ceiling coverings. The color of the surroundings depends upon the spectral character of the illuminant. A yellowish paper may appear the

same under a deep yellow light as a yellower paper under a pale yellow light. The object of these remarks is to illustrate that there is some scientific or physical basis for discussing any alteration of the color of artificial light tending away from daylight in color.

Inasmuch as amber glass is often used as in the foregoing, it is of interest to analyze it. The author

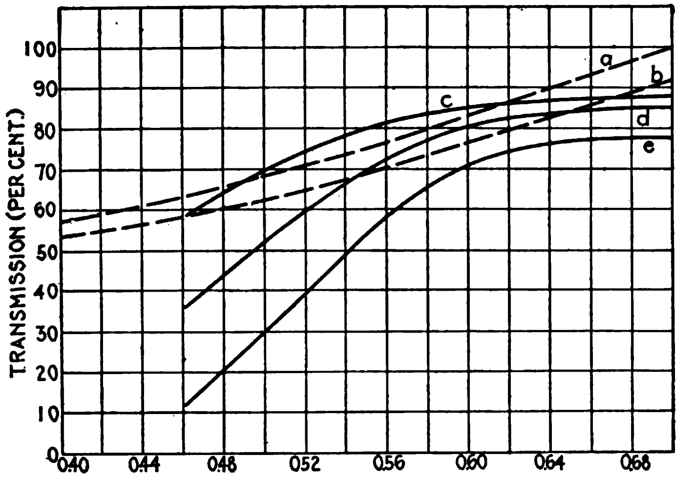

Fig. 108.—Screen for altering tungsten light to the same spectral character as carbon incandescent electric light. c, d, e show the transmission curves of amber glasses of different densities.

has considered it unsatisfactory for the above purpose because of its greenish tinge, and has therefore sought for a yellowish glass or dye without this greenish tint. Inasmuch as amber glass is usually used for the purpose of altering the present illuminants to a color approximating the yellow light of the carbon filament lamp, kerosene or candle flame, let us take the case of altering the light of a tungsten lamp operating at 7.9 lumens per watt to the color of the old carbon lamp operating at 4 w.p.m.h.c. This

can be done at a loss of not more than 20% of the total light; that is, the tungsten lamp operating at 1.25 w.p.m.h.c. will, with a yellow screen, produce light closely approaching that of the above carbon lamp at about 1.5 w.p.m.h.c. Thus light similar in color to carbon incandescent lamp light can be obtained at a high efficiency with the tungsten lamp.

Curve *a*, Fig. 108, represents the transmission curve of an ideal screen for altering the tungsten

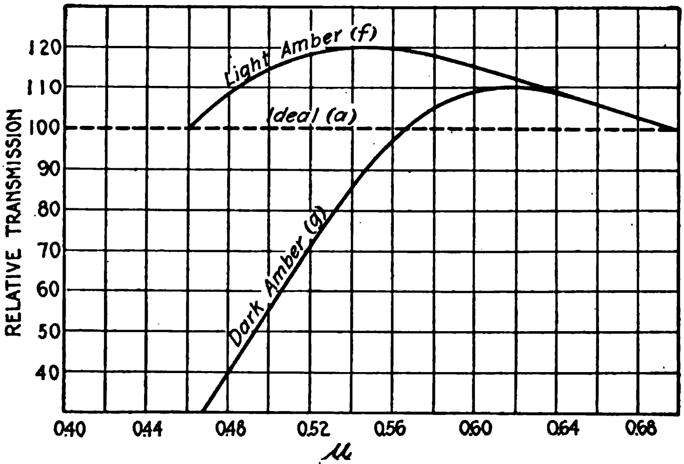

Fig. 109. — Comparison of ideal screen *a*, Fig. 108, with amber glass.

light to a spectral character close to that of the old inefficient carbon lamp. Curve *c* is the transmission curve of a light-density sample of amber glass. Curves *d* and *e* are the transmission curves of thicker specimens of the same amber glass. Curve *d* is the result of reducing curve *a* at all points by 8%. It is seen that the amber glass is far from ideal, there being an excessive transmission of green light compared with the ideal curve *a* (or *b*). As the density or thickness of the amber glass is increased the transmission of green rays decreases relatively more than

the yellow, orange, and red rays; that is, the dominant hue shifts toward red, which is apparent by casual observation. In Fig. 109 the transmission curve of the ideal yellow glass for the above purpose is plotted as a straight dashed line, and the transmissions of light and dark amber glasses relative to those of the ideal screen are plotted as shown. It is seen here, expressed analytically, what careful observation indicates to be true: that amber glass is far from ideal for altering modern illuminants to a color similar to that of the older illuminants which many claim to be the more æsthetic.

By means of present day tungsten lamps used with a proper colored screen the light of the kerosene flame can be closely imitated at efficiencies from 5 to 10 lumens per watt depending upon the efficiency of the unaltered source employed. The light of the old carbon incandescent lamp can be imitated in the same manner at efficiencies from 7 to 13 lumens per watt. The author has treated this subject elsewhere.[24]

Screens for this purpose are readily made by the use of dyes, although they will in general lack permanency. Most yellow dyes are objectionable for the above purpose for the same reason as amber glass. Potassium bichromate is, under moderate conditions, a permanent yellow. To this may be added a pink dye, which will usually yield a combination which is satisfactorily yellow. For the pink some very dilute red dyes may be used. Rhodamine is satisfactory in color, but is very fugitive under the influence of light and heat. Many yellow dyes are quite permanent if used on a sheet of glass instead of directly on the lamp bulb, but usually these must be corrected as already indicated.

Much pleasure can be derived from the use of

tinted illuminants, for they lend themselves to decorative effects and afford an easy means for eliminating monotony in lighting. Two- or three-circuit pendant units (preferably indirect or semi-indirect) are convenient for this purpose, for by using clear and colored lamps various combinations of color and intensity can be obtained which are very pleasing. Silk shades of various tints are readily applied to lamps, and colored gelatines are easily concealed and afford a ready means of obtaining pleasing colors. (Colored media are discussed in the last chapter.) Very brief descriptions of a few uses of colored light in interiors may aid in showing the possibilities of such application of the art and science of color. There are many indications that we are at the beginning of an age of color appreciation. It has already asserted itself in modern painting; and the gorgeous display of color that greets the visitor to such magnificent architectural structures as the Congressional Library in Washington and the Allegheny County Soldiers' Memorial at Pittsburgh indicates that this century is likely to witness a renaissance in the use of colors in decoration. Color was the keynote in the plans of the Panama-Pacific Exposition [19] much of which is obtained by lighting effects. Colored jewels reflecting millions of images of light sources, colored flames, moving color filters, and lights of various colors were woven into a gorgeous spectacle. W. A. D'a Ryan, who planned the color effects, has also used the 'scintillator' with considerable success. Powerful searchlights arranged to point radially upward illuminate clouds of steam in various colors. The beams diverge from each other in a fan-like manner. The possibilities in spectacular lighting are manifold.

A notable use of colored illuminants is found in the Allegheny County Soldiers' Memorial. In this splendid lighting installation, which was designed by Bassett Jones,[20] mercury arc lamps, tungsten incandescent lamps, Moore tubes, and yellow flaming arcs were used. The ceiling of the auditorium, which is sixty feet above the floor, is composed largely of glass in decorative panels. The central panel is outlined by means of the pinkish light of the nitrogen tube. Over the corner panels yellow flame arcs are hung, and their flicker adds charm to the colored ceiling which would not be present with perfectly steady light sources. The outer panels are lighted by the bluish light of mercury arc lamps, and tungsten lamps stud the ceiling, adding a touch of brilliancy. The contrasting of colors is so harmoniously accomplished that the result is exceedingly artistic. Thus the beauty of this monument of decorative art is visible at night as well as by daylight, which is too often not the case. There are many other interesting applications of color which make this beautiful work of art a worthy mecca for those interested in color and lighting.

Art galleries offer excellent opportunities for introducing the science of color lighting. As already mentioned, more than four hundred colored tungsten lamps were used with clear tungsten lamps in correcting the lighting of a temporary art exhibit. The results were extremely encouraging, inasmuch as they met with the approval of artists and critics alike. This was perhaps the first notable attempt ever made to furnish illumination of a daylight quality for lighting paintings. This field offers a splendid opportunity for development, which can readily be done by means of the color-correcting lamps and accessories now available.

Many artistic effects can be obtained by the use of colored light in the home. A slight rose or orange tint in the light is very pleasing and attractive, although the choice of tints is of course a matter of taste. A rather interesting case is found in a dining room of a pretentious residence. A large oval panel of diffusing glass is set into the ceiling, and behind this a great many red, green, and blue lamps of low voltage are placed in the approximate proportions of two red, three green, and five blue lamps. The lamps of different colors are controlled by means of dimmers set in the wall, so that by varying the proportions of red, green, and blue light various qualities of light may be obtained and also a large range of intensities.

A person who enjoys color can readily devise many simple schemes for obtaining tinted light. An experiment which the author found of interest was the production of an artificial moonlight effect. A high decorative window in the living room was removed and placed in the normal position of the storm sash, thus providing space for tubular lamps in reflectors. The window was covered on the inside with a cardboard of bluish-green tint and in the opening before the window, a stained wooden lattice was placed, over which an artificial rambler rose was twined. The lamps, which were tinted a light blue-green, illuminated the bluish-green cardboard, which as viewed through the foliage produced a charming effect of moonlight. As the space was narrow the cardboard was not uniformly bright, owing to the proximity of the lamp, but this defect was readily overcome by stippling the surface with a black watercolor. Such effects are readily applied to bay windows and other convenient places.

Many possibilities present themselves to those

interested in color lighting. The many colored media available and the diversity of the color of commercial illuminants provide the means for carrying out many ideas. Electrically excited gases, such as carbon dioxide, neon, helium and mercury vapor, contained in glass tubes, are commercial possibilities which have not yet been applied to the fullest advantage for elaborate colored effects. In the average case, however, requirements are readily fulfilled by means of ordinary light sources and colored media.

66. *Color Preference.*—It may be of interest here to record the results of some simple experiments, inasmuch as such data may indicate eventually the effect of the illuminant upon our preference for certain colors and may throw some light upon the relation of lighting to the pleasing effect of colors. The experiments represent the beginning of an investigation begun with an object in view which is discussed in Chapter XV but are described here as a matter of interest. The Zimmerman colored papers were used, but as there was no saturated green paper one was dyed and placed in the series. This is designated as *q*, the other letters indicating the catalogue designation of the various colored papers. Fifteen colored papers, each four inches square, were spread out haphazardly upon a white surface, the individual papers being from six to ten inches apart. The observer was asked to study the colors and pick them out in the order of his preference. He was asked to isolate the individual colors from everything as far as possible, choosing the color for color's sake alone. In other words, if possible he was not to associate the colors with wearing apparel or anything else. The experiments were carried out under ordinary tungsten light (7.9 lumens per watt) and also under daylight

entering the window, in the latter case no direct sunlight being present. The intensity of illumination in each case was of such value as would be considered sufficiently high for viewing saturated colors. The two observations were carried out at least a week apart and usually several weeks intervened. The general consistency of the preference orders of the

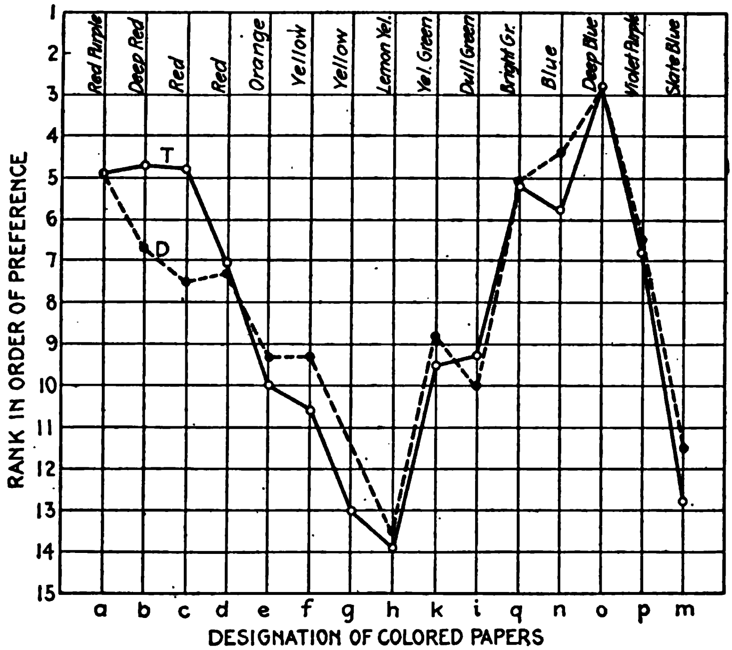

Fig. 110.—Showing the preference or rank of a number of fairly saturated colors.

fifteen observers was somewhat surprising. The mean results are plotted in Fig. 110, the ordinates representing color preference. There may be some question regarding the legitimacy of the definition of color preference, but the procedure adopted here provides a simple means of plotting the data. There being fifteen colored papers, the least preferred would be placed last and ranked fifteen, the highest

preference therefore being unity. It is seen that the least preferred colors were those of highest luminosity and in general of lowest saturation. That is, purples and highly saturated colors having hues corresponding to the regions near the ends of the visible spectrum, namely blue and red, were definitely favored. This confirms a conclusion previously arrived at from other observations.

According to E. B. Titchener[21] there are two types of observers: one type prefers the saturated colors and the other definitely prefers unsaturated or 'artistic' colors, but the former type constitute a majority. The author's observations indicate that, when colors are chosen for 'color's sake' alone, the saturated colors are almost invariably chosen. E. J. G. Bradford,[22] in experimenting with twenty-six university students with a set of fifteen papers each about 30 inches square, found that saturated colors were most preferred. He also found that the admixture of a small proportion of another color lowered the position of the color in the preference order. Cohn[23] has also contended that increase of saturation tended to make a color more pleasing. Bradford found that the order of preference remained reasonably constant by performing the same experiments on three observers after an interval of two weeks and again after a lapse of twelve months. The subject of color preference will be treated further in Chapter XV, but it may be of interest here to compare the results obtained by Bradford with those obtained by the author. In the latter's experiments nearly all the colors were as saturated as possible, while only the first eight of Bradford's were 'pure.' Bradford does not state the character of the illuminant used, but presumably it was daylight, so the daylight preference

order taken from Fig. 110 is used for comparison in Table XX.

TABLE XX

Color Preference

Rank	Bradford	Luckiesh
1.	Dark blue	Dark blue
2.	Saturated green	Blue
3.	Chocolate-brown	Red-purple
4.	Pale blue	Green
5.	Slate blue gray	Violet-purple
6.	Saturated crimson	Deep red
7.	Pale green	Orange-red
8.	Coffee-brown	Crimson
9.	Bluish green	Dull yellow-green
10.	Ink-red	Orange
11.	Cinnamon-brown	Orange-yellow
12.	Pale pinkish brown	Dull green
13.	Bluish green	Slate blue gray
14.	Pink	Yellow
15.	Yellowish Green	Lemon-yellow

A word of caution is necessary regarding drawing conclusions from Table XX. The colors are described so indefinitely and the two series of colors differed very much. In one series practically all colors were as saturated as it is possible to obtain them by means of pigments, but in the other series about half of the colors were tints and shades. For instance, in the latter series chocolate-brown is a saturated red of a dark shade. Furthermore, as seen by Fig. 110, the reds ranked fairly high, but in placing them in order, as in Table XX, they are near the middle of the list because several colors ranked just above them. Notwithstanding the foregoing there is a similarity in the two preference orders. Fig. 110 serves as an indication of the similarity of the preference order of the various observers. For

instance, there being 15 colors if every observer placed *h* (lemon-yellow) last, its rank would be 15. The mean rank for *h* was nearly 14, indicating that nearly all the observers placed it last. Dark blue was placed first by most of the observers.

As far as the limited results indicate, there was no general difference in the preference orders under the tungsten light and daylight, excepting under the former illuminant the reds were definitely placed higher in the preference order than in daylight. This has seemed apparent from previous observations as well as the indication that of a series of saturated colors the most saturated are usually the most preferred. There is some indication from other experiments that the relatively few who prefer tints instead of saturated colors, when asked to choose the colors for color's sake alone, are those that are unable to overcome the tendency to associate the colors with other things. It is just this associational preference order that is of more interest in this chapter. That is, in lighting there is no doubt that tints are more proper or more æsthetic. The data which is discussed in Chapter XV from the viewpoint for which they were obtained are inserted here merely to illustrate some points in the matter of color preference. The data on this subject are rare and the danger of drawing definite conclusions at the present time is clearly recognized.

Observation during the past few years has led the author to conclude that in the matter of color preference for color's sake alone, the colors near the ends of the spectrum and the purple series are in general favored. Artificial illuminants are usually poverty-stricken in blue and violet rays. Therefore these colors can probably be made to appear more

attractive by means of an illuminant having more blue and violet rays and less red and orange rays than ordinary artificial light. Strictly, the artificial daylight already described is in general the correct artificial illuminant, but experiments indicate that, in the illumination of colors for pure decoration, a 'white' light in which violet and red rays predominate produces very pleasing results. A glass of this character was made of a proper density so that white objects had the same white appearance as under natural skylight, yet such color as the pinks, purples, blues, violets, deep reds, appeared richer. Inasmuch as in the decorative use of color, exactness in hue is not usually essential, and as the color is employed for our pleasure, it is legitimate to use the illuminant that produces the most pleasing result. It is well to have white objects appear white, yet if those colors which please us most can be made more pleasing by the use of 'white' light of such a spectral character as described above, it is within the province of the lighting expert to use such a light. Cobalt-blue glass, in the absence of a specially made glass, will produce these results fairly well if chosen of proper density. An ultramarine blue screen used with ordinary artificial light will produce an extreme 'white' light of this character. Prussian blue added to it forms a satisfactory screen for this purpose. In prescribing such an illuminant one is not committed to the opinion that the pigments used in ordinary decoration are not 'rich' enough to begin with. Such handicaps are not uncommon in many of the arts employing color, and furthermore colored decorations are often dimmed by exposure. In any event the matter is one that will be governed largely by taste and the adoption of such a lighting procedure as

indicated above is legitimate if it pleases those concerned.

The foregoing experiments are not described here with the intention of suggesting that saturated colors should be used in lighting. They could not be used without endangering the appearance of many colors. These various comments have been made with the object of suggesting fields for thought and experimenting. Of course it is realized that the matter of color preference is exceedingly complicated by all the phenomena of color vision and environment, yet the foregoing experiments are instructive if the limitations of the results are recognized.

67. *A Demonstration Booth.* — The most effective manner of studying and demonstrating lighting effects is found in the use of a booth specially designed for the purpose. Having employed such a booth for several years very successfully it appears of interest to describe one in detail. A number of different types have been constructed, but the one described here has been most successful. In Fig. 111 is shown the wiring diagram covering the principal features. The dotted line enclosing a rectangular space represents the front dimensions of the booth, the center being represented by the maltese cross. The lamps represented by the larger circles are placed in their relative positions. Fourteen clear 40-watt tungsten lamps indicated by numbers were spaced as shown around the inside of the box near the front side, thus providing light from various directions. These are controlled by a contact arm arranged to rotate. The control apparatus is diagrammatically shown at the right, spread out for convenience. These switches are actually placed in a small recess in the right end of the box, as shown in

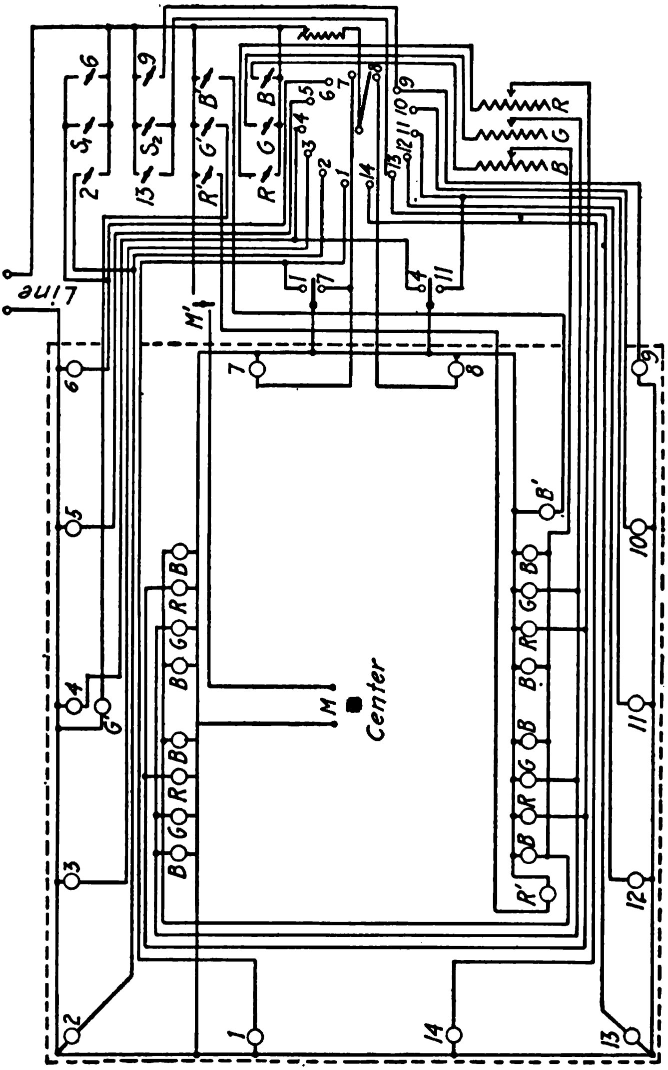

Fig. 111.—Wiring diagram of an experimental and demonstration booth.

Fig. 112. Twelve snap switches are shown above the rotating contactor, of which the upper six control clear lamps as indicated by the numbers. The middle switches S_1 and S_2 in the upper two rows control, respectively, the four lamps on the left and right.

These must be special switches and the wiring connections have been omitted for the sake of simplicity. The clear lamps are very useful in demonstrating effects of light and shade and for showing the effect of diluting colors, or decreasing their saturation, for which purpose a variable resistance is placed in series with the rotating contactor. Two single-pole double-throw switches are shown at the left of the rotating

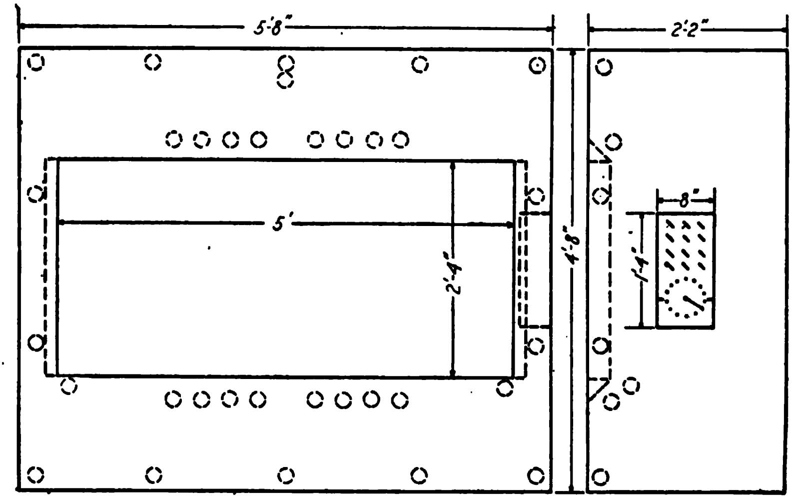

Fig. 112.—Showing dimensions and locations of lamps in the demonstration booth.

contactor switch, which provide for quickly changing the lighting from above to below or from the left to the right side. A motor *M*, controlled by switch *M'*, is placed on an extension at the back of the booth, so that its elongated shaft can be projected through the back side in the center. (A motor operating on direct or alternating current and capable of rotation at a very high speed is desirable.) On this rotating shaft such experiments as those indicated in Figs. 14, 23, 29, 30, 31 are readily performed.

General lighting of many colors can be obtained

on the objects placed at the center of the back from the rows of colored lamps — eight above and eight below — by controlling the relative intensities of the red, green, and blue lights by the corresponding rheostats indicated at the right. The switches controlling these lights are *R*, *G*, and *B* in the bottom row of the twelve snap-switches at the right.

The purity of the primary colors is of great importance. These can readily be made satisfactory by any one acquainted with coloring materials and the science of color-mixture. Perhaps the easiest procedure in most cases is to begin with a set of lamp colorings. Gelatine filters made as described in Chapter XVI may also be used; however, for demonstration purposes colored lamps provide a more compact apparatus, although in the latter case constant care of the lamps is necessary, owing to the fading of the colorings due to heat and light. By using the rheostats the mixing of colored lights can be done on a white diffusing surface hung on the back of the booth at the center, which provides a very satisfactory means for the synthesis of colors. The effects of quality of light on colored objects can be readily demonstrated, and daylight effects can be easily shown by adding blue-green light to the clear tungsten light. In fact practically any demonstration involving color-mixture is possible with such an apparatus.

Single red (R'), green (G'), and blue (B') lamps controlled by corresponding switches on the right, are placed as shown at the angles of an equilateral triangle, the green lamp being placed at the upper apex. Interesting colored shadow demonstrations are easily shown, the shadow experiment illustrated in Fig. 28 showing the primaries, complementaries and

white light having been developed for use with these lamps. Many of the effects described in this book, especially those in Chapter XII, have been developed in the booth just considered. Other electric circuits are also used, but these will readily occur to the experimenter. Two views of the booth are shown in Fig. 112 with dimensions. Those interested in such a field will find the use of such a booth exceedingly interesting and instructive. A number of booths, perhaps not as compact and universal, have been used by pioneers in the study of color effects. Several years ago Basset Jones, a pioneer in the art of lighting, employed such an apparatus in very interesting demonstrations.

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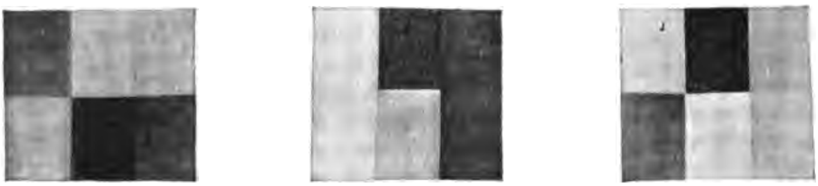
CHAPTER XII

COLOR EFFECTS FOR THE STAGE AND DISPLAYS

68. *The Stage.* — It is not the intention to treat the use of colored light in stage and display effects as they have been practised heretofore, but to point out some interesting new possibilities that have been developed by the application of the science of color. By the use of red, green, and blue lights any desired color effect may be produced, but the purity of these primary colors is very important. Apparently there has been little exact science of color-mixture applied to the stage. It is true that wonderful effects have been produced, but it is just as certain that the possibilities in color effects have scarcely been touched upon. The color effects of today have not passed beyond the play of colored lights upon colored scenes in a more or less haphazard manner, the final effects, which are often very attractive, being arrived at by a 'cut and try' method. Examination of colored media used for such effects show that very often impure colors are used. In fact, satisfactory commercial colorings are rare, and it is usually necessary to alter them in order to obtain colored lights of satisfactory purity. As already stated, only pure primary colors—red, green, and blue—are essential for producing a large variety of colored effects.

Colored effects are based upon the principle that the appearance of colored objects depends largely upon the spectral character of the light which illuminates them; that is, the color of an object is not

inherent wholly in the object itself. Things are visible only by virtue of the light which passes from them to the eye. For instance, a red fabric appears red because it has the property of reflecting only red light. Obviously, if red rays are not present in the light under which the fabric is viewed, it will appear black. Colors can be made to disappear on a light background if they are sufficiently pure and free from 'black' by viewing them through a glass of proper color. Pale blue lines on white paper will practically disappear under a deep blue light, and red pencil marks on white paper will be invisible under



(Red light) (Green light) (Blue light)

Fig. 113.—Illustrating the effect of colored light upon the appearance of six colored papers.

a pure red light of proper color. This principle has been applied in stereoscopic drawings, the picture for one eye being printed in blue-green ink and that for the other in red ink. On placing a blue-green glass before one eye and a red glass before the other, a stereoscopic effect is produced.

In Fig. 113 are shown the relative brightnesses of six colored papers under red, green, and blue lights, the colored papers being in the same relative positions in each group. The photographs were made through a very accurate filter specially made for the panchromatic plate used (Fig. 90), and therefore the brightnesses are shown as nearly in true relation to each other as the limitations of photographic repro-

duction permit. It is interesting to note some of the changes; for example, the two middle colors reverse in brightness when respectively illuminated by red and green (or blue) lights.

Carrying this principle further the author[1] has developed some colored effects which show promise of application as the applied science of color becomes more thoroughly understood and as the cost of producing suitable colored light decreases. In making these applications it must be remembered that a color is only completely defined when analyzed into the three factors, hue, saturation, and brightness. For the purpose of producing the disappearing effects to be described, a simpler analysis can be used. That is, it is convenient here to consider separately the hue of the light that the pigment reflects and the amount it reflects, the first involving the spectral hue and the latter its brightness (or value). A group of colored patches on a gray ground can be made to disappear — that is to become indistinguishable from each other and the background — when the colored patches are illuminated by light of such a spectral character that they reflect rays of exactly the same character and in equal amounts as the background. This condition will not hold for another illuminant; therefore, some of the colored patches will be distinguishable under another illuminant. This disappearance can be produced in another manner. By using a light of such character that the colored patches will reflect practically none of it they will disappear if placed on a black or dark gray background. Both methods have been used in developing these colored effects. The success of the scheme depends largely upon the choice of pigments properly related to each other and to the colored lights employed. Pure

transparent pigments are quite essential. In mixing the colors it is necessary to understand the principles of color-mixture, for in mixing pigments there is always a tendency toward black (Fig. 20). A large supply of pure pigments is desirable, so that a pure pigment may be selected instead of obtaining the necessary hue by mixture. For example green can be made by mixing yellow and blue-green. This subtractive method often results in a green plus black;

Fig. 114.—Illustrating the changing of scenery by the use of colored lights.

that is, a muddy green. If the green can be obtained directly as a pigment instead of by this mixture, the black component is not present. Attention to these finer points is what distinguishes the scientific colorist from those who arrive at results without heeding the fundamental principles. Owing to the confused state of color terminology and the indefinite notation of pigments, it is impossible to describe accurately how these disappearing effects are produced. They involve the science of color and can be produced readily if the principles are thoroughly understood.

The modern tendencies toward the use of color and color effects point to great future possibilities in the application of the science of color. Already in some European theaters the stage scenery has been revolutionized, and lighting effects are playing a greater part in the drama than heretofore. The experiments described below suggest the possibility

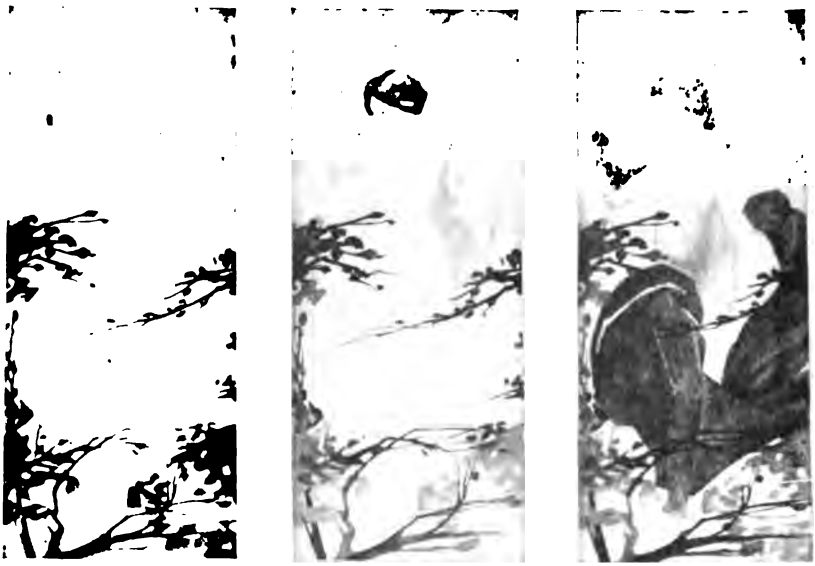


Fig. 115.—Illustrating the disappearing effects produced on a specially painted scene by varying the color of the illuminant.

that rays of light, swift and noiseless, might take the place of some of the present-day cumbersome methods of scene-shifting. Possibilities are also suggested for representing the supernatural, heretofore unrealized on the stage. In Fig. 114 are shown, as well as can be represented in black and white, two appearances of a mountain scene. The mountain and entire background can be made to disappear at will by changing the color of the illuminant. The

appearance on the left is that under the ordinary yellowish light from tungsten incandescent lamps. The other appearance is that under an orange-red light. The colors in the foreground are violets, grays, blues, greens, and touches of yellow. Those in the background are white, yellow, orange, red, and pink. Lightning effects can be obtained by flashing reddish light on the painting. No attention was paid to congruity in the use of colors, for the painting was designed merely to illustrate the possibilities of the scheme. Further striking effects can be obtained by the use of illuminants of other colors, especially pale blue-green light. Thus a scene can be changed by rays of light. It is also possible to make the mountain disappear and in its place to have some other scene appear, for instance a seascape.

In Fig. 115 the first picture appears to be a Japanesque arrangement of foliage. This is the appearance under a deep orange-red light. Gradually, by introducing blue light, the figure appears, and on adding green light or clear light it appears fully in view. On extinguishing the red component in the illumination the figure, and especially the flowing robe, stands out in strong contrast and beautiful effects are produced by changing gradually from blue-green to a deep blue. By gradually introducing orange-red light and extinguishing the other components the figure slowly disappears. Such effects show the possibility in scenic effects in fairyland plays. It is well to understand that the photographic reproductions just shown only illustrate the brightness contrast. In the originals the contrasts are more striking, because they are due to differences in hue as well as in brightness. In fact, it is difficult to illustrate in black and white the effects produced with this

particular subject, because in the center illustration most of the contrast is due to differences in hue alone.

Another changing scene that was produced is that of a summer landscape gradually merging into a snowy wintry scene. By painting the body and branches of the trees a gray, and covering these and the ground with a bluish-green foliage, they appear in their abundant garb of summer under ordinary light. By changing the color of the illuminant to a 'cold' pale blue-green the summer foliage disappears from the trees and from the ground, and barren trees and a ground covered with snow appears. These are the chief features of this scene. Of course touches of color added judiciously here and there greatly enhance the beauty of the scene. Many other effects have been produced, but no attempt has as yet been made in applying them on a large scale in stage scenery. However, the problem in the theater is comparatively simple owing to the perfect control of the illumination. Certainly the possibilities of such applications of the science of color are very extensive. Only the simpler ones have been described here, owing to the necessity for demonstrating the principle as simply as possible. The more elaborate effects require more perfect interrelation of colors and illuminants. A field not to be overlooked is that of legerdemain, in which such disappearing and changing effects should prove valuable.

69. *Displays.* — The foregoing effects are also applicable for advertising displays. In fact, it is strange that colored light has not been applied more to illuminated signs. Large tungsten lamps equipped with color filters and operated on flashers should add considerable to the attractiveness of ordinary scenic signs. The filters could be such as to produce moon-

light, daylight, and sunset effects upon a scene with great effectiveness. Colored lights pursuing each other in waves around the border of a sign represents a very simple application of colored light in adding movement to an ordinary illuminated sign. It seems that the introduction of changing and disappearing effects on illuminated signs should become popular, owing to the lower cost as compared with the cost of an elaborately wired sign studded with incandescent lamps. There is no doubt that the latter signs are visible at a greater distance, but there are a large majority of signs that cannot be viewed from a

Fig. 116.—Illustrating a flashing sign produced by properly relating the hue and brightness of the pigments with the colors of the illuminant.

great distance owing to obstructions. In Fig. 116 is represented a possibility outrivaling the ordinary illuminated sign, for actual disappearing effects are produced. The copy in the first view is in red, orange, and pale yellow. This disappears under orange-red light, the whole surface appearing of a uniform tint. The copy in the second view is in blue-green. On illuminating the sign with ordinary tungsten light the sign appears as in the third view. By alternating with this clear tungsten light an orange-red light the copy shown in the first view appears and disappears. By alternating with the clear light a blue-green light the copy shown in the second view

disappears and appears. Thus various effects can be produced. This is a very simple sign, requiring a most simple wiring scheme. The flashing lettered sign has also been effectively combined with a scenic painting. Practically an endless variety of effects can be produced as rapidly as desired. Many other effects have actually been produced, such as a smiling and frowning face, a gesticulating speaker, a waving flag, and a rotating wheel, by this method of changing the spectral character of the illuminant. These have been widely exhibited.

This scheme has already been applied in displays. The haphazard play of colored lights upon colored patterns not designedly chosen is productive of catchy attractiveness; however, the actual disappearing effects are more striking. For window displays the copy is placed in a darkened recess resembling the demonstration booth described in #67 so that it is protected from extraneous light. The colored lights are operated by flashers designed to bring about the proper sequence of appearances. Such demonstrations have been built and successfully operated. Successful experiments have been carried out with the color effects appearing by transmission through translucent glass, in this case the colored lights being behind the glass. The colored scene or pattern is painted in transparent colors related as before on the back of the glass. It is also possible to project the colored light from a distance by means of parabolic reflectors, which would be an advantage in some cases for out-door displays.

From the foregoing simple illustrations several advantages in the scheme are obvious. Apparent motion is obtained without elaborate wiring or mechanical devices excepting the usual flasher. Copy

can be changed continually if desired or a sign can be repainted often. The greatest difficulty lies in the initial preparation of the colors in proper relation as to brightness and hue. In order to produce elaborate effects it will perhaps be necessary to use water colors or carefully prepared oil paints, protecting these with a covering of weatherproof varnish. The only expense involved in the change of copy is in the painting of it, for the color scheme can always be retained in proper relation to the colored illuminants. A flashing sign of this character is very simple, and the possibilities of scenic effects are greater than in any other method, simplicity being taken into consideration. The scheme adds to the possibilities of stage effects where it can be carried out with ease and sometimes be employed to supplant the jarring interruption due to shifting scenery. Of course the necessity of screening extraneous light if present will be a disadvantage in the application of this scheme to out-door displays, but there are many places where this will be unnecessary, because numerous bill-board sites can be found where there is little or no scattered light.

The possibilities of the use of colored light in applying the science of color to displays, advertising and stage effects, have barely been touched. With the increasing efficiency of light production the utilization of color in lighting effects will become more elaborate.

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CHAPTER XIII

COLOR PHENOMENA IN PAINTING

70. *Visual Phenomena.* — The artist has often shown an antipathy toward science, apparently under the impression that art goes further than the mere mixture and grouping of colors and shadows and produces effects beyond scientific explanation. By no means is it contended here that art can be produced by 'rule of thumb,' or by scientific formulæ. Nevertheless, facts are the basis of all art and, while scientific investigation has not yet revealed all its hidden secrets, scientific explanations can be presented for many supposedly mysterious effects. It is proposed in this chapter to present the results of analyses and to indicate that science has been a great aid to art, and that it will perhaps render a much greater service in the future.

The artist is in reality a link between two lightings. He endeavors with chisel or brush to record an expression of light. The record is therefore an expression of light. Inasmuch as both the original scene and the painted record make their appeal through the visual sense, it is well to inquire into the process of vision. Seeing involves the discrimination of differences in light, shade, and color. In the ordinary sense no eye ever sees more, and no painting however 'soulful' has more for its foundation, than differences in light, shade, and color. (In the general sense white, gray, or black are colors of complete unsaturation and varying brightness. It will perhaps

CHAPTER XIII

[illegible]MERA IN PAINTING

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Plate IV. Illustrating the effect of spectral quality of the illuminant. Daylight, below; ordinary artificial light, above

be more convenient in this chapter to use the terms 'colors' and 'values' but with a clear understanding that the term 'color' is here used in a restricted sense and that value is in reality included in the term 'color' as used heretofore. See Chapter IV.) The fundamentals of a painting therefore are colors and values. It is by grouping these elements that the artist makes his appeal to emotional man. However, science can aid the artist by analyzing the influences which alter these fundamentals.

It took the artist many years to learn that the eye is far less perfect in definition than a simple lens and screen. In other words everything in the whole visual field is not seen distinctly at the same time. Definition is best at the point of the retina where the optical axis of the eye meets it, but outside of a small area surrounding this point, objects are not seen distinctly. Further, the eye sees only the beginning and end of an ax stroke and it does not see all the movements of a galloping horse or splashing water. Photography was hailed by many as being a useful means for recording a scene. But photography has done much to teach the artist what he should not paint — and that is the realistic picture recorded by the photographic plate. Thus it is seen that material facts are often represented by artistic lies; that is, in reproducing a scene the artist does not record what he knows to be there, but rather what he *sees*. Instead of recording details over the whole scene, the artist's task is to paint what the *eye* sees and in addition, by a sort of legerdemain, to record in colors and values, as far as is within his power, the impressions gained through the other senses. Thus the problem grows more complex, departing from the physical and entering the physiological and psycho-

logical realms. The physical laws are comparatively well understood, but the phenomena underlying the other fields are still hazy, owing to the lack of sufficient experimental data. In viewing a painting the problem becomes still more complex, for what the observer sees in a painting he must largely supply himself through the associational mental process.

There are many vague terms used by artists, perhaps definite to those who use them, but the lack of systematic usage is confusing. It has been seen that the eye is far from being a perfect optical instrument. One of its faults is chromatic aberration; that is, an inability to focus different colors at the same time (#33). Naturally when viewing a group of different colors the eye is focused for the brighter colors. The eye is also constantly shifting under normal conditions. We are not conscious of these minute involuntary movements, but this shifting surely influences the appearance of paintings. The effects of after-images are also of importance (#43). If one views a red line on a green or blue ground, the effect is that of unrest. Both colors may not be exactly in focus at the same time, but perhaps of greater importance are the effects of overlapping after-images caused by involuntary eye-movements, which result in a 'lost edge.' The latter effect is sometimes very striking at the horizon of a landscape painting. The after-image caused by a green stimulus is an unsaturated purple or pink. At the edge where green foliage meets a gray or pale blue sky a hazy pink fringe is often seen. The eye, in shifting slightly up and down, causes an overlapping of these after-images (approximately complementary to the original stimulus), thus forming a 'lively' edge. The result of an after-image sometimes is to alter the saturation

as well as the hue of a colored area. The phenomenon of simultaneous contrast (# 44) is very influential, and of course is carefully studied by the artist. This effect of one area upon another is of considerable magnitude under some conditions. Two adjacent colored areas can mutually so influence each other that they each appear differently in hue, saturation, and brightness than if viewed separately. On considering these influences and those due to intensity and spectral character of the illuminant, it becomes evident that no color has any definite and fixed appearance after it is out of the tube. These are facts which should be of great interest to the artist. Indeed, the great artists understood some of these influences very well. Most artists recognize many of them, but in general some of the influences are unknown to the vast majority of painters. These various phenomena are treated elsewhere. (See Plate III.)

71. *Lighting.*—Light has been termed the soul of art. The body of a landscape consists of the material things, but as Birge Harrison states, 'its soul is the spirit of light — of sunlight, of moonlight, of starlight — which plays ceaselessly across the face of the landscape veiling it at night in mystery and shadow, painting it at dawn with the colors of the pearl-shell, and bathing it at midday in a luminous glory.' But of scarcely less importance is the lighting of the painted record of an expression of light. In various chapters it has been shown what a great influence the illuminant exerts on colors and values — the very essence of a painting; however, slight attention has been given to this important factor.[1] The lighting artist should be to art what the musician is to music. His duty is to render the color symphony as the

composer intended it to be rendered. This only can be done exactly by lighting the work both as to distribution and spectral character of light just as it was lighted when the artist gave to it the final touch. This of course is impossible, but it is easy to light it by an artificial daylight which will render its appearance more nearly that which is had when completed by the artist, and to overcome certain limitations of pigments by properly distributing the light. (The

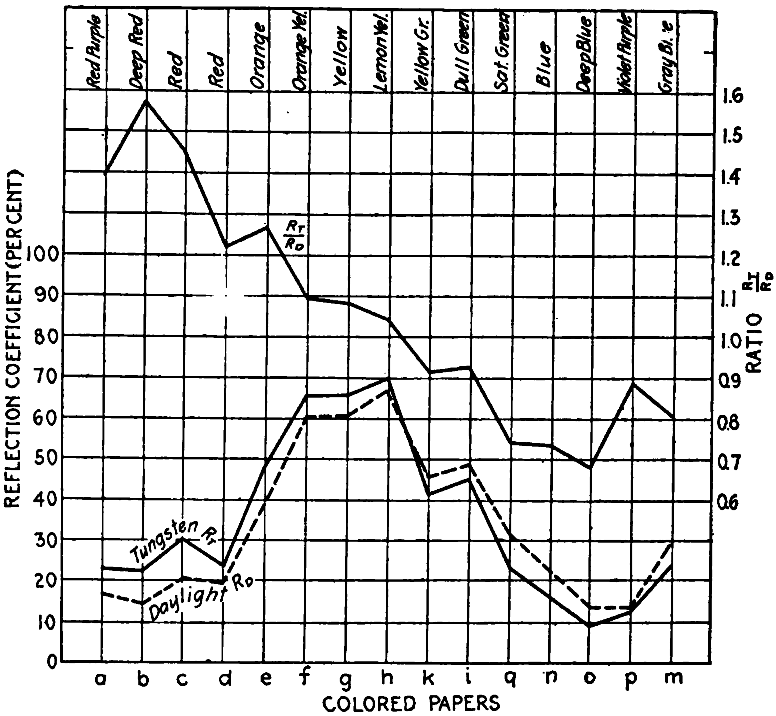

Fig. 117.—Showing the reflection coefficients of fairly saturated colors for daylight and tungsten incandescent electric light. (See Table XV.)

influence of the illuminant is seen in #42, 68, and Table XV.) Not only does the spectral character of the illuminant alter the hue, but likewise the brightness or value. In Table XV it is seen that pigments

differ tremendously in reflecting power or relative brightness when illuminated with daylight and ordinary artificial light. These data have been plotted in Fig. 117 to emphasize this important point. The reflection coefficients of the various colored papers for daylight are shown by the dashed line R_D and for the light from a (vacuum) tungsten lamp operating at 1.2 w.p.m.h.c. by the full line R_T. The ratios of the reflection coefficient under tungsten light to that under daylight are shown by the upper curve. It will be noted that those pigments which predominantly reflect red, orange, or yellow rays are considerably brighter under the tungsten light than under daylight, but those pigments which predominantly reflect violet, blue, and green rays are brighter under daylight. The curve shows that these ratios vary from 0.69 to 1.57; that is, some of these pigments change in relative 'value' more than 50 per cent. However in painting, the relative 'values' of adjacent and other areas are of importance, and such changes in relative brightness are often as high as 100 per cent. For instance, assume that clouds are adjacent to an area of blue sky in a certain painting and that these pigments are represented respectively by *e* and *n*. The ratio of the brightness of the clouds to that of the sky is 1.6 when the painting is illuminated by daylight. Under the light from the tungsten lamp this ratio is 2.8 or nearly doubled. In fact cases have been found where such ratios have doubled, as will be seen later. The hue changes are in some cases enormous, but these cannot be readily shown here. The artist recognizes the difficulty of painting under artificial light, yet he apparently does not raise his voice in protest when his work is illuminated by artificial light. In Fig. 118 are shown the effects of

(Daylight) (Tungsten light) (Orange-red light)

Fig. 118.—Showing the effect of the illuminant upon the appearance of a colored frieze.

different illuminants upon the values of a frieze painted with ordinary water colors. The illuminants were daylight, ordinary tungsten light (vacuum incandescent lamp), and an orange-red light. In this frieze the upper rectangles were alternately tinted a reddish purple and a bluish purple. The lotus flowers and buds were tinted a pale blue, the stems, dark green, and the alternate sectors of the lower circular patterns were colored respectively a yellowish orange and a reddish orange. The background was white. An extreme example is shown in Fig. 113. An example of the difference in the appearance of a painting under natural and ordinary artificial light is shown in Fig. 119 (see Plate IV). A photometer was used to measure the relative brightnesses of adjacent patches of pale blue sky and pale yellow clouds at about the center of the sky area in this picture, indicated by the circle. Under tungsten light the two patches were of equal brightness, but under daylight — the light under which practically all paintings are done — the patch of sky was *twice* as bright as the adjacent clouds. The filter used in taking these photographs was quite accurate, so that the values are faithfully represented. It is seen that the sky was much brighter than the foreground when the painting was illuminated by daylight. It is only fair to state that the difference in foregrounds is due somewhat to the lack of sufficient range of gradation in the photographic paper. Note also the relative brightnesses of the low-hanging clouds. If a painting will stand such enormous changes in the relative 'values' of its parts (and the accompanying changes in hue), it is indeed flexible. Under most artificial illuminants the hues in a painting shift toward the red as compared to their appearance under daylight

(Daylight)

(Ordinary artificial light)

Fig. 119.—Showing the effect of the spectral character of the illuminant upon the values of a painting.

illumination. That is, a deep yellow appears orange, a bluish purple appears a reddish purple, blues and violets approach gray, and the reds are relatively brighter. Accompanying this shift in hue is a corresponding shift in brightnesses or values. That is, yellow, orange, and red appear brighter, and violet, blue, and green appear relatively less bright, as shown in Fig. 117.

The distribution of light on a painting has a great influence upon the expression of the painting. Measurements show that the range of relative brightnesses in a landscape is often as high as five hundred to one. That is, the brightest spot (for instance, cumulus clouds receiving direct sunlight) are often several hundred times brighter than the deepest shadow. The pigments employed by the artist will not record such a physical contrast. In any landscape painting the brightest spot is seldom more than forty times brighter than the darkest spot when both receive practically the same amount of light as is usually approximately the case. A white paper is no more than fifty times brighter than a so-called black paper. In order to overcome this handicap due to the limitations of pigments the artist may resort to illusions if possible. For instance, a highly illuminated red object is not painted red but an orange-red, because it is true that under intense illumination colors appear less saturated. Thus, by painting the highly illuminated red object an orange-red, the illusion of intense illumination is produced. A hot desert scene is depicted in the same manner, with the additional illusion of short or minimal-length shadows. Thus the feeling that the sun is at the zenith helps to produce the illusion of a hot desert scene.

R. W. Wood performed an interesting experiment

in accentuating contrast in a painting by projecting a positive lantern slide image of a painting upon the original in exact coincidence. In this manner the high lights received relatively very much more light, and the shadows less light than in the ordinary case, where the painting is uniformly flooded with light. This scheme, though interesting and instructive, cannot be used in practise. Extensive experiments on the effects of distribution of light over paintings indicate that a proper distribution is a legitimate and an effective aid to the artist in bringing forth the proper expression of a painting. In Fig. 120 are shown some effects of different distributions of light on a painting, although the limitations of the photographic process prevent a very satisfactory illustration of these effects. It is seen, however, that the mood can be changed enormously by altering the distribution of the light. The scheme is difficult to carry out in cases where the wall space is crowded with paintings, and it is unfortunate for various reasons that such crowded conditions must exist. However, the principle is easily applied to individual paintings, and at the same time a correction of the light to daylight quality can be made. This has also been carried out in the case of trough lighting, which is often a practical and convenient procedure, because most paintings have their chief high lights in the upper portion. The predominant light can be directed from a point in the trough near the middle of the upper edge or near one of the corners of the painting, depending upon the requirements. This has been found very effective. The lighting of paintings depends also upon the hanging, which is too often done with a view toward keeping the bottom edges on a horizontal line instead of with a view toward placing

Fig. 120.—Effect of distribution of light on the expression of a painting.

them in the proper position for lighting and observing them. The wall covering is of importance and should be a dull, neutral, diffusing surface and preferably rather dark from a lighting viewpoint. This prevents undue annoyance from its image, as seen in the glass coverings of pictures on the opposite side of the room. The illusion produced by dark surroundings is striking, and there are many who advocate such wall coverings; however, others contend that the appearance of a gallery so hung is unæsthetic. Much could be written on the daylighting of galleries. There have been some extensive studies of the problem made in various countries, but there is no general agreement so far as quality of light is concerned. Some advocate southern exposure, others a northern exposure. In general, artificial light is more readily controlled than daylight, and therefore lends itself more readily to obtaining proper effects.

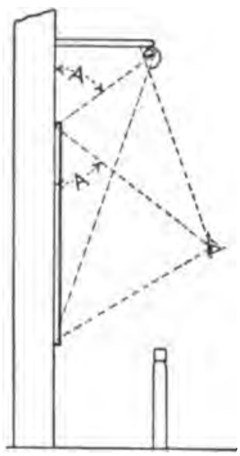

Fig. 121.—Illustrating the optics of picture lighting.

Inasmuch as paintings are very often poorly lighted, a simple illustration of the geometrical principle of lighting is shown in Fig. 121. Every problem is readily solved by such methods. In the design of the lighting, both natural and artificial, it is well to determine graphically the positions of the light sources and the expanse of skylight (if the latter be diffusing), so that images of these bright sources cannot be reflected from the glazed surfaces of paintings directly into the eyes.

72. *Pigments.* — A number of satisfactory pigments, among which are vermilion, indian-red, and

the ochres, are derived from minerals; the animal kingdom supplies such pigments as carmine and sepia; and a large number of pigments, such as indigo, gamboge, and madder, are derived from the vegetable kingdom. Many of the aniline dyes are derived from coal tar. Many pigments are made artificially, such as ultramarine, cobalt-blue, zinc-white, Prussian-blue, chrome-green, and the lakes. The natural pigments derived from minerals are prepared by calcining and grinding and are purified by washing. For oil painting these pigments are ground in such vehicles as linseed or poppy oil. For water colors the medium is usually gum water. The latter fixes the pigments on the surfaces to which they are applied and serves as a varnish. Such vehicles should preferably be colorless, because, for instance, the yellow color of linseed oil is likely to impart a greenish tinge to pale blue pigments. Turpentine is used as a thinner for oil paints. Varnish is employed to protect pigments from destructive agents usually present in the atmosphere and from marring by abrasion. Oil varnishes are less liable to crack than spirit varnishes, and the quality of a varnish depends largely upon the resin of which it is composed. (See Chapter XVI.)

There are three general classes of pigments used in paintings. The pastel pigments are quite destructible. Water colors lend an airy delicacy to a painting and are quite appropriate in some classes of work. They are difficult to use, owing to their transparency and to the change in color that they undergo on drying. Oil colors, which according to some authorities were first used in canvas painting in about the year 1400, are the most durable — an important and necessary property of pigments for use in painting. Many pigments are permanent under moderate illumi-

nation when used alone, but there is always the danger of interaction between pigments when mixed. The permanency of the older paintings is no doubt due in part to the fact that the palette was rather poverty-stricken many years ago. Today there are several hundred pigments available, and therefore there is considerable danger of mixing pigments that interact. Anyone who has searched for pigments that are permanent under excessive illumination and heat will perhaps readily agree that the permanency of pigments is only a matter of degree and that under severe conditions many so-called permanent pigments readily deteriorate. Gases and coal dust in the atmosphere and especially the products of the combustion of illuminating gas are known seriously to affect pigments. Light has a bleaching action and paintings often turn yellow when kept in the dark. A simple method of restoring paintings is to clean them with a cloth and set them in the sun for a day or two. This treatment, however, is rather severe for water colors and modern lake colors and is only satisfactory in some cases. Doubtless tests are being made continually on the permanency of pigments, but there are few available data on the subject. In general mineral colors are more stable than vegetable colors. Gases, moisture, interaction, heat, and light are the common causes of the deterioration of pigments. It has been found that most pigments are more permanent in vacuo, protected from harmful gases and moisture. Some of the results of experiments indicate that the destructive rays in sunlight are chiefly the violet and ultra-violet rays; that is, pigments have been found to deteriorate practically as quickly under blue glass as under clear glass. However, the most commonly used blue glass, namely cobalt-blue, trans-

mits deep red and infra-red rays almost as freely as clear glass, so it is possible that heat was responsible for some of the deterioration. Of the great number of available pigments the following are found to be most durable:—

Indian-red, largely ferric oxide;
Venetian red, iron oxide;
Burnt sienna, calcined raw sienna;
Raw sienna, a clay containing ferric hydroxide;
Yellow ochre, hydrated iron oxide;
Emerald-green, a mixture or compound of copper arsenate and acetate;
Terra verte, a natural green pigment found in Italy;
Chromium oxide, green;
Cobalt-blue, usually a mixture of the arsenate, phosphate, or oxide of cobalt with alumina;
Ultramarine ash, now made from soda, sulphur, charcoal, and kaolin.

Pigments are far from spectral purity; that is, they reflect light of many wave-lengths. Interesting data obtained by Abney are shown in Table VI and spectrophotometric analyses of a number of these pigments, including those just described as being quite permanent, are shown in Figs. **122** and **123**. It is seen that the mixing of colors is complicated owing to the complexity of the spectral character of the light reflected by pigments. For the sake of clearness it will be noted that the reflection curve of a neutral tint (white or gray) surface would be a straight line parallel to the base line in the last two illustrations. The colorist should be somewhat familiar with the spectral characteristics of his pigments, because such knowledge is very useful in mixing pigments. The production of different hues by mixing pigments is possible because pigment colors are not

monochromatic, that is, not of spectral purity. For instance, suppose monochromatic pigments were avail-

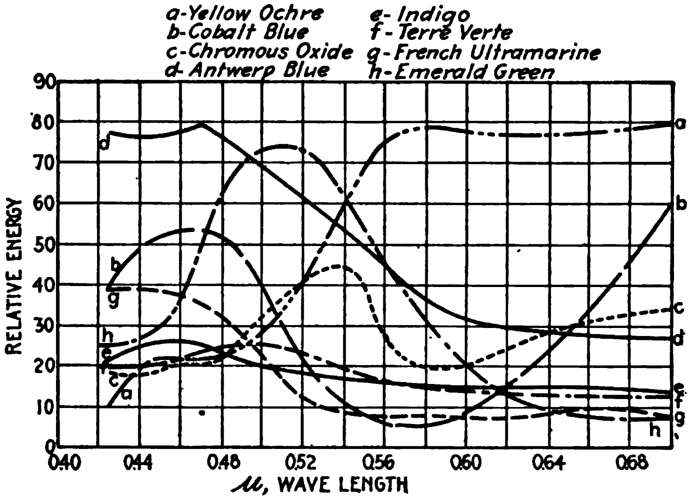

Fig. 122.—Spectral analyses of pigments.

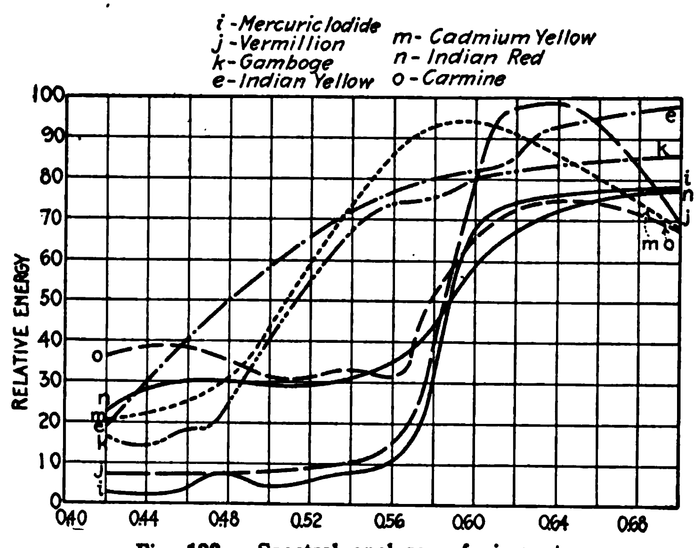

Fig. 123.—Spectral analyses of pigments.

able and yellow and blue were chosen for mixing. Instead of obtaining green from the mixture, black

would be obtained, because the light transmitted by pure yellow flakes would be a monochromatic yellow which would not be transmitted by pure blue flakes; thus by the combination no light would be transmitted. One virtue of the poverty-stricken palette is the scanty possibility of the interaction of pigments; however, such a palette cannot be the source of a large variety of highly luminous and pure colors.

Where high brightness and full saturation are desired it is well to avoid the production of the desired hue by mixture, as far as possible. This can

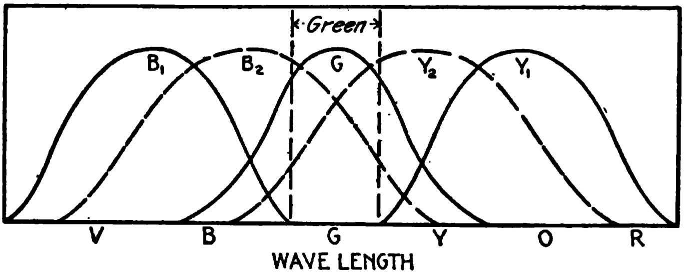

Fig. 124.—Illustrating the effect of the amount of the green components in blue and yellow pigments on the amount of 'black' in the mixtures.

be illustrated by means of the mixture of blue and yellow. When these pigments are pure their mixture must result in the production of black. For instance, suppose the two pigments transmit light rays respectively as shown diagrammatically by B_1 and Y_1 in Fig. 124. Neither pigment transmits green rays nor does one pigment transmit any rays that are transmitted by the other; therefore the resultant transmission will be zero and 'black' results. If the so-called blue and yellow pigments are less pure, they may be found to transmit some green rays. These may be represented diagrammatically as B_2 and Y_2 in Fig. 124. It is seen that the resulting mixture of these two pigments will be a green of rela-

tively low brightness corresponding to a green to which 'black' pigment has been added. The greater the proportions of green rays transmitted or reflected by the two pigments, the less 'black' will be present in the green resulting from their mixture, or, more correctly, the brighter the resultant mixture will be. Obviously, if the two components are selected successively closer and closer to green, finally the limit-

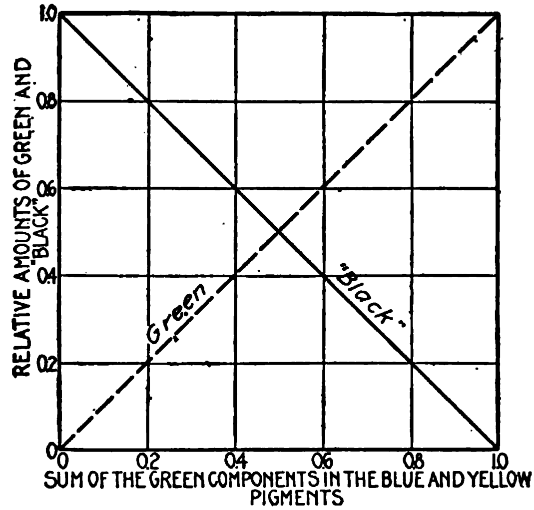

Fig. 125.—Diagrammatic illustration of the results of mixing blue and green pigments containing various amounts of green.

ing case would be that in which both components were green, G, and their mixture of course would produce green. The results of such a theoretical procedure are shown diagrammatically in Fig. 125, where the sum of the green components in the blue and yellow pigments is assumed to vary from zero to 100 per cent; meanwhile the amount of green in the mixture varies from zero to 100 per cent, and the amount of 'black' from 100 per cent to zero. This simple diagram illustrates a very important point in

the mixture of pigments. For the reason that the subtractive method of color-mixture always tends toward the production of 'black' it is well to have available a large number of fundamental pigments representing as many hues as possible. This is especially desirable in the production of effects described in Chapter XII. Before the advent of modern art such a stock of pigments was not essential because the tendency in the past was not to employ colors as pure as those found in common use today. A study of the curves in Figs. 122 and 123 is recommended in connection with the discussion presented in connection with Figs. 124 and 125 in order to obtain an idea of the relative brightnesses of various mixtures. See Chapter XVII.

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CHAPTER XIV

COLOR MATCHING

73. Nearly all the phenomena influencing the appearance of colored objects have been treated elsewhere, but inasmuch as color-matching is a special art and is also of interest to everyone at times, a summary of those factors that influence the appearance of colors may not be out of place. The expert colorist is fully aware of the influence upon the appearance of a color of retinal fatigue or after-images, surrounding colors, difference in sensibility of various parts of the retina, the spectral character and intensity of the illuminant, the surface character of the fabric, the peculiarities of dyes, and other factors. Everyone has encountered difficulties in distinguishing or matching colors. For instance it is difficult to distinguish some blues under ordinary artificial light, owing to the relatively low intensity of these rays. Many colored objects that have appeared pleasing in daylight are so changed under artificial light as to be quite unsatisfactory. Usually under artificial light the dominant hue of most colors shifts toward the longer wave-lengths. For instance, some purples will appear quite red under artificial light and bluish under daylight (Fig. 80). Such an example is methyl-violet.

The surface character of a fabric plays an important part in the appearance of the color. A colored fabric is ordinarily seen by reflected light, the light falling upon it being robbed of some of its rays

by the selective absorption of the dye. If the surface is porous like wool, the light can penetrate deeply and will therefore suffer more internal reflections (# 64), finally reaching the eye quite pure in color. The degree of transparency of the fiber also exerts an influence. It is seen that such dichroic dyes as methyl-violet, cyanine, and dilute solutions of rhodamine or eosine pink will be very much influenced by the surface character and composition of the fiber. Wool and silk fibers are transparent, but those of cotton are not, hence light cannot penetrate as far into the latter as into silk or wool. Therefore, when these three fabrics are dyed in the same solution of a dichroic dye such as methyl-violet the cotton will appear bluer than the other fabrics. The finish of the surface is also of importance, because of the reflection of unchanged light which dilutes the colored light of the fabric. Many aniline dyes exhibit the property of fluorescence, which alters the appearance of the fabric under different illuminants. A fabric colored with such a dye will appear differently at grazing incidence than when viewed normally to the surface. The actual distribution of light is of importance for the last two reasons.

74. *The Illuminant.* — Inasmuch as the appearance of a color is so influenced by its environment, the question might be asked, Under what conditions is its appearance considered standard? Daylight has always been the accepted standard, because the arts have developed under daylight. Furthermore daylight of a certain quality is considered white light; that is, it has no dominant hue. Such an illuminant is logically a better standard than an illuminant which of itself will impart a definite hue to the colored fabric. The color of an illuminant (the color of a white sur-

face) is largely a matter of judgment which is influenced by many factors, and, inasmuch as daylight is quite variable, there has been a lack of agreement as to a standard daylight. Some have taken a white mist as representing such a standard, others have insisted upon the adoption of clear noon sunlight, and some have advocated the integral light from the sky and noon sunlight. Nevertheless a great many colorists have adopted north skylight for color-matching.

The difference between sunlight and skylight is demonstrated on viewing objects in the sunlight. Colors receiving direct sunlight appear 'warmer,' and the shadows which receive only light from the blue sky appear of colder hues, although this comparison is not wholly justifiable, because of the difference in intensity. Of course the relative intensities of sunlight and skylight vary considerably, but on a clear day a shadow on a white blotting paper, which receives light from the unobstructed blue sky, is only one-fifth or one-sixth as bright as the portion of the paper receiving both direct sunlight and skylight. The color of daylight varies throughout the day (#62). Many colorists favor the use of daylight in the forenoon, although the morning light is often of a pinkish tint. On cloudy dark days a purplish tint is often quite noticeable. Anyone engaged in accurate color discrimination is aware of the continual changes in the spectral character of daylight. Smoke and dust also alter daylight toward a reddish hue, and it is likely that the conditions in the upper stratum of the atmosphere vary from time to time, producing a variation in the character and amount of scattered sunlight. The influence of colored surroundings in altering the color of daylight is very important. Clouds, adjacent buildings, green foliage, and the color of interior

walls exert a very noticeable influence on the color of daylight. Perhaps the most annoying feature of daylight is its unreliableness. In some climates the actual hours that a satisfactory daylight is available for color-matching are few. In congested and smoky cities this useful period is further reduced, so that there has always been a demand for an 'artificial daylight.' Satisfactory units of this kind are now available (#62), since the advent of highly efficient steady light sources such as the gas-filled tungsten lamp. It is of course impractical to furnish an artificial daylight to match the different kinds of daylight, to which various colorists have become accustomed. It is too much to ask any manufacturer to supply artificial daylight which will exactly match daylight, altered by reflection from adjacent colored objects, which will be different in most cases. If, however, an artificial daylight is available to fill the demand of the colorist, he should be willing to compromise and give the unit a fair test. If it differs slightly from the daylight to which he is accustomed, yet shows no peculiar spectral characteristics, the colorist can readily adapt himself to the slightly altered conditions. If the artificial daylight is composed of indestructible color-screens the colorist can be assured that he has an invariable standard that will serve him twenty-four hours a day — a most desirable characteristic. There is some advantage in the production of a colored glass screen for use with tungsten lamps because the quality of light can be varied between sunlight to blue skylight by varying the temperature of the lamp filament. As was shown in #62 the glass developed by the author alters the light from the vacuum tungsten lamp operating at 7.9 lumens per watt to noon sunlight quality; however,

when used with the gas-filled lamp operating at about 16 lumens per watt, artificial skylight is produced. This is a very convenient method of utilizing the same glass to produce artificial daylight of different kinds. Spectrophotometric tests afford the only thorough means of analyzing an artificial daylight. Dichroic dyes and some mixtures of aniline dyes are greatly influenced by the spectral character of the illuminant and therefore afford a ready means for determining approximately the satisfactoriness of an illuminant for color-matching purposes. Such mixtures can be readily made so that fabrics dyed with them will appear of the same hue under a certain illuminant, yet under another illuminant they will appear quite unlike. The two dyes used in screens *c* and *d*, Fig. 17, are examples of this character. Mixtures that appear green under daylight but quite different under another illuminant can be readily made by mixing naphthol-yellow with acid-violet and an orange with a deep bluish aniline dye. Two blue dyes can be readily made to appear practically alike under daylight, one consisting of a rather pure blue and the other having the common characteristic of transmitting deep red rays. Under an artificial illuminant, rich in red rays, the latter will appear quite reddish as compared to the former. A weak solution of erythrosine or rhodamine when added to a weak solution of potassium bichromate will produce a yellow in artificial light; however, in daylight it will appear quite pink. Such combinations can be readily produced by examining the spectra of the dyes and by combining them judiciously. Excellent dichroic dyes are methyl-violet and cyanine. These striking instances of the effect of the illuminant are well known to dyers and other colorists.

75. *The Examination of Colors.* — In examining colors it is well to understand the peculiarities of vision. The *fovea centralis* of the retina, where vision is most acute, is directly opposite the middle of the pupillary aperture. A small area around this point has been named the *macula lutea.* The center of this region, which is called the 'yellow spot,' owing to its color, often manifests itself in the examination of colors (# 55). It apparently absorbs blue rays somewhat, and its effect is quite noticeable on viewing bright colors. The effect is particularly noticeable roughly outlined in after-images produced by large bright colored areas. Bright colors are difficult to examine, owing to retinal fatigue and to the prominence of after-images and successive contrast. This annoyance can be reduced by decreasing the intensity of illumination or by the use of neutral tint glasses. These methods are perhaps questionable, but are certainly less objectionable than the use of blue-green glass, as is used by some for the examination of bright red and orange colors. Paterson[1] recommends the use of a gelatine film dyed with malachite green (a blue-green) for the examination of such highly luminous colors. A practically neutral tint screen can be made of a solution of nigrosine in gelatine.

The effect of simultaneous contrast is often very great, for colors are apparently altered in hue and brightness by the influence of an adjacent color (Plate III). A black pattern on a red ground will appear of a blue-green tint. A white surrounded by green will appear brighter and of a pinkish tint. Chevreul[2] published an extensive work on this subject many years ago which goes into elaborate detail concerning contrast. In order to examine the

color of a thread or portion of a variegated color pattern, it is well to isolate the portion to be examined by means of a gray mask. The effect of contrast is so great that a colored thread may appear rich and pure in one pattern, yet quite dull amid other surroundings. This effect cannot be overlooked without inviting trouble in color-matching.

If it were not for the effects of fluorescence, color-matching glasses could be used which have been especially adapted to the artificial illuminant. However, as many of the aniline dyes fluoresce they should receive light of the standard daylight quality while being examined. This would not be the case with the combined use of an artificial illuminant and correcting spectacles. Of course the intensity of the artificial light must be several times greater than ordinarily required for seeing in order to compensate for the unavoidable absorption of the color-matching spectacles. This scheme is not new, for it has been practised in special cases by many expert colorists.

Colored fabrics are examined both by transmitted and reflected light. Colors are usually viewed by reflected light, the change in the color of the incident light being due to selective absorption. In a loose fabric of porous surface the light penetrates more deeply and is colored by many multiple reflections. As already stated silk and wool fibers are more transparent than cotton, and therefore permit a deeper penetration of the light. This means a greater number of multiple reflections, and, for example, as in the case of a dichroic dye, it results in a color corresponding to that which would be obtained with a cotton fabric dyed in a denser solution of this dye. The luster of silk is attributed to the smoothness of

the fibers. In examining colors by reflected light the distribution of the incident light is of importance inasmuch as some of the regularly reflected light is but slightly changed, owing to the fact that it does not penetrate the fabric. This tends to dilute the colored light and to make it appear less saturated. In installing artificial daylight it is well to distribute the light in a manner found satisfactory in daylight.

Many aniline dyes in solid form reflect light complementary in color to that which they transmit. Crystals of some purple dyes appear green by reflected light. If the crystal be ground into a fine powder, the latter appears purple in color, because the light penetrates it and by transmission and multiple reflections appears different than by specular reflection. A borax bead containing cobalt may appear almost black, but when ground into a powder it appears blue. Pigments when in a dense homogeneous mass are quite opaque and reflect light selectively. The phenomena of surface color is intimately related to the coefficient of absorption and the refractive index of the substance. Inasmuch as the phenomenon is not of sufficient importance to go into details regarding it, the reader is referred to any standard text-book in physics for an analysis of the phenomenon. Some fabrics exhibit changeable colors owing to their nap, which ends in a certain direction. If it ends toward the light, the latter penetrates the fabric to a considerable depth and is deeply colored by multiple reflections. If the nap ends away from the direction of the light, there is more specular reflection and therefore less penetration, which results in a smaller change in color.

The fibers of a fabric may be considered to hold

the dye in a state of suspension or solution, and therefore fabrics are sometimes examined by transmitted light. In a special case of this kind of examination the fabric is held between the eye and the light and is viewed at a grazing angle. This is sometimes called the overhand method. By thus looking through the fibers, hues can be distinguished that are quite imperceptible in an examination by reflected light. This method is especially applicable to the examination of colors of the darker shades. The rich appearance of these dark colors viewed in this manner is very striking.

The change in color that a dyed fabric undergoes on drying is of great importance and often quite annoying. This need not be treated here, because the novice will learn very quickly that dyes in solution and freshly dyed fabrics often undergo great changes in color. It is a point to be considered in color-matching. A great many dyes exhibit the property of fluorescence, among which are the eosines, phloxine, rhodamine, uranine, fluorescein, rose bengal, naphthalin-red, resorcin-blue, and chlorophyl. In matching strongly fluorescent colors it is seen that there is quite a difference in hue between the reflected and transmitted light. For instance, by reflected light an eosine pink will appear redder than by transmitted light by the overhand method. This is due to the fact that the reddish fluorescence is most predominant in the light reaching the eye when the fabric is examined by the ordinary method of reflected light. By the overhand method this fabric will appear decidedly bluer, owing to the fact that the fluorescent light does not reach the eye in appreciable amounts. This effect may readily be demonstrated by dyeing two fabrics respectively by fluorescent and

non-fluorescent dyes so that they match by reflected light. They will be found to appear different by the overhand method.

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CHAPTER XV

THE ART OF MOBILE COLOR

76. This subject will be treated from two viewpoints: first as to the relation of colors and sounds, and second, from the viewpoint of an art of mobile color independent of any other art. The treatment from the first viewpoint is not entirely one of choice. In fact one feels compelled to discuss the possibility and justification of such a relation because in the few instances that colors have been related to sound music the superficiality has been quite apparent. It took centuries of scientific study and analysis to mould musical chaos into a uniform art of measured music, and even today there are composers who are not reconciled to the generally accepted state of affairs. Even with this example of slow evolution in sound music before them, there have been a few who have had the temerity to relate colors and music before the public notwithstanding the meager data available. It is significant that the names of these 'inventors' are not found among the experimental psychologists and other investigators who are unearthing information that may some day form the foundation of an art of mobile color.

Rimington, in a book entitled 'Colour-Music,' repeatedly compares colors and sounds, owing to the fact that both 'are due to vibrations which stimulate the optic and aural nerve respectively.' He further states that 'this in itself is remarkable as showing the similarity of the action of sound and color upon

us.' He presents other 'similarities' but in fairness it should be noted that he states that too much weight should not be given to them. Nevertheless, owing to the repeated citations by Rimington of these 'similarities' one concludes that they influence him considerably in developing his so-called 'color organ.' If no stronger reason for interest in the art of mobile color existed, space would not be given to a discussion of this subject, but there are indications that such an art is waiting to be evolved. Furthermore, the relation between sound and color forms such an insignificant part in the author's thoughts regarding color music, that space would not be given to such a discussion if it did not appear necessary to clarify the matter by dispelling some of the superficial ideas regarding such a relation and by pointing out the limitations of certain attempts to present such a combination.

There is no physical relation between sounds and colors. Sounds are transmitted by waves in a *material* medium, as proved by many experiments. Light rays are *supposed* by many to be transmitted by a *hypothetical* medium called the ether, but scientists are divided in their opinions regarding the *existence* of an ether. Furthermore, the two kinds of wave motion that are used to represent sound and light waves are *necessarily* different, because the former cannot be polarized while the latter can be. Light waves pass through what we term a vacuum, but sound waves cannot. These few fundamental differences are sufficient to illustrate the futility of any claims that sounds and colors are produced in similar ways.

Next let us consider the respective perceiving organs. The ear is analytic, for a musical chord

can be analyzed into its components. This is not true of the eye. In other words, the eye is a synthetic instrument incapable of analyzing a color into its components. Many examples have been cited in previous chapters of colors that appeared identical to the eye, yet differed greatly in spectral character. This difference in the two organs must necessarily influence the choice of a fundamental mode of producing 'color music.'

As already stated, it is noteworthy that those few persons who have actually written 'color-music' are not found among the large group contributing to the development of the science of experimental psychology or to sciences closely akin to it. The relation between colors and sound music, if any exists, some day will be revealed, but only through systematic experimentation by investigators well versed in physics, physiology, and psychology. There is value in experiments directly relating colors and music, but certainly it is too early to experiment before the public. Such procedure jeopardizes the chance for ultimate success, but, fortunately, past exhibitions of this character will have been forgotten long before color-music evolves into a form in which it will be recognized ultimately.

For some time the author has been interested in the subject of mobile color as a mode of expression similar to the fine arts, and has therefore watched with interest some attempts in relating colors and music. This interest has been almost entirely in an art of mobile color independent of any other art, but, besides preliminary experiments bearing on the subject, some experiments with colors and music have also been performed. These will be touched upon later. Recently a musical composition by A. Scria-

bine entitled 'Prometheus' was rendered by a symphony orchestra with an accompaniment of colors according to the 'Luce' part as written by the composer for the 'Clavier à lumières' (Fig. 126). No clue is found in the musical score regarding the colors represented by the notes in the 'Luce' part, or the

Fig. 126.—The 'Luce' part for the 'Clavier à lumières' in Scriabine's 'Prometheus.' (Upper staff in each portion is the 'Luce' part.)

manner in which a 'colored chord' is to be played—whether by juxtaposition or by superposition. The latter point is of fundamental importance, inasmuch as the eye is not analytic and a mixture of the colors of a 'color chord' results in only a single hue. Some of those responsible for the rendition of this music, with color accompaniment, had, at different times previous to the final presentation, accepted both the Rimington scale and Scriabine's code (the latter having been discovered later in a musical journal published at the time of a previous presentation of the same selec-

tion in London) as being properly related to the music. The acceptance of the Rimington scale, in the absence of Scriabine's code, as being adapted to the music, and the final acceptance of the latter code, which was used in the public presentation, shows that at the present time there is no definite relation between colors and sound music, even in the minds of artistic interpreters of music. It must not be assumed that the colors in Table XXI bear any absolute relation to the corresponding musical notes. Rimington's scale apparently was chosen arbitrarily, as shown, merely for convenience in writing a 'color score.' This is probably true of Scriabine's scale. Those familiar with the science of color would hardly consider it probable that a composer of sound music would hold the key to 'color music' when they freely acknowledge their helplessness in definitely relating colors and musical sounds. Everything pointed to failure, and if one may judge from the criticisms of the rendition of 'Prometheus' with the accompaniment of colors, after allowing for a considerable degree of conservatism and inertia, the relation of the colors and musical sounds was indefinite, unsatisfactory, and distracting. Considering that the experimental work has not yet been done which should form a basis for expression and arousing emotion by means of colors, no other outcome of superficially relating colors to sound music could have been expected. Even though this be an extremely progressive age, it is not likely that color music can evolve, in an acceptable form, from the imagination of a few persons.

77. While it appears that the art of mobile color must evolve from fundamental experimental data

TABLE XXI

Color Codes

Rimington		Scriabine
C	Deep red	Red
C#	Crimson	Violet
D	Orange-crimson	Yellow
D#	Orange	Glint of steel
E	Yellow	Pearly blue and shimmer of moonshine
F	Yellow-green	Dark red
F#	Green	Bright blue
G	Bluish green	Rosy orange
G#	Blue-green	Purple
A	Indigo	Green
A#	Deep blue	Glint of steel
B	Violet	Pearly blue and shimmer of moonshine
C	Invisible	

on the 'emotive value' of colors, of simultaneous and successive contrasts in brightness and hue, of sequences in hues, tints, and shades, of rhythm, etc., it is interesting also to experiment with colors in relation to music. However, a safe elementary procedure in the latter experiments is to use colored light merely to provide the 'atmosphere' and gradually to introduce the element of varied intensity and, possibly, rhythm. Certainly it is far less presumptuous to use color in this manner in the absence of experimental data than to attempt to play a 'tune' in colors as a part of a musical score. If it is only a matter of individual taste, any procedure is, perhaps, legitimate, but when the object is to develop an art of mobile color only cautious procedure is commendable. In providing 'atmosphere' for a particular motif such superficial associational relations as blue-green for rippling water and red for fire (because artists paint

them thus) are insufficient. It is the deeper emotional relation that is desired which, perhaps, cannot be determined with certainty without many careful experiments on a large number of subjects.

In developing an independent art of mobile color, what procedure shall be adopted? Certainly the fundamental experiments will be found to lie largely in the realm of psychology. The aim of the modern artist is not totally unrelated to the subject, and a group of such artists perhaps would form a most interested audience for such experiments. The new movement in the theater which is striving for harmony in action, lighting, and setting is not wholly unrelated to the subject under consideration. In experimenting with colors for the purpose of developing an art of mobile color it may be profitable and encouraging to study the evolution of sound music. In Baltzell's 'History of Music' we read

'When we think of music we have in mind an organization of musical sounds into something definite, something by design, not by chance, the product of the working of the human mind with musical sounds and their effects upon the human sensibilities. So long as man accepted the various phenomena of musical sounds as isolated facts, there could be no art. But when he began to use them to minister to his pleasure and to study them and their effects, he began to form an art of music. The story of music is the record of a series of attempts on the part of man to make artistic use of the material which the ear accepts as capable of affording pleasure and as useful in expressing the innermost feelings.'

The leading principles in music are rhythm, melody, harmony, and tone quality, and in the execution of a musical composition dynamic contrast is an essential factor in expression.

'For ages after the birth of music, rhythm and melody were the only real elements, rhythm being first recognized. Music

that lacks a clearly-defined rhythm does not move the masses. It was not until harmony appeared that music was able to claim a position equal to that accorded to poetry, painting, sculpture, and architecture.' 'These principles, rhythm, melody, and harmony, became, when couched in the forms of expression adopted by the great masters, what we call modern music, and the story is one of a development from extreme simplicity to the complexity illustrated in modern orchestral scores.'

The lesson we gain from the foregoing is to proceed patiently. Sound music had an elementary beginning evolving into its present form only after many centuries of experiment.

A thought that naturally comes to us is this: Is there anything in Nature that suggests color music? Perhaps scenes full of color are suggestive of 'atmosphere' colors for musical compositions. Perhaps if the cycle of appearances of such a scene throughout a day were compressed into a period of five minutes, it might suggest what a composition in color music would be. Being unaccustomed to thinking of color apart from form, perhaps such studies would be fruitful. Certainly at first, in thinking of color for color's sake alone, one has a feeling that all solid foundation has been removed from beneath him.

When it comes to experimental work one feels that the foundation has been restored, but is appalled at the immensity of the work to be done. The available psychological literature yields some interesting information. Some work on affection pertaining to colors has been done, and the studies of rhythm are very extensive; however, the work, which eventually will form a definite basis for developing an art of mobile color, has hardly been begun. The meager data in color preference partially described in #66 were obtained as a beginning of an inquiry into some of the elementary impressions produced by colors.

It appears from this work, which supports conclusions arrived at by others, that in general saturated colors are more preferred than tints or shades, the latter perhaps being generally more preferred than tints. There is some evidence that subjects who are less capable of isolating the colors, that is, more inclined to associate them with other experiences, prefer the tints and shades or so-called 'artistic' colors. Some study has been made of combinations of colors, but without definite results at the present time. Of course all the known principles of harmony and contrast of colors are available for use by the pioneer in the art of mobile color. However, no application of these principles can be made until extensive experiments have been performed. The 'emotive value' of various hues, tints, and shades, of simultaneous and successive contrasts in hue and brightness, and of rhythmic sequences in hue and brightness must be determined. Bradford found that saturated colors were most preferred and that the admixture of small proportions of another color have a lowering effect upon the preference of a color. Regarded objectively, the pure colors were found first in the preference order while those which appear to be adulterated with another color, were placed last. Cohn had previously claimed that increase in saturation tended to make a color more pleasing. Titchener obtains results of a similar nature with the majority of his subjects, who definitely reject tints and shades of colors in favor of the saturated colors. While a color may be most highly preferred among a large number of colors the 'emotive value' of this color is perhaps rather low as compared with many other things. For instance a dark blue color may be distinctly more preferred than any other color in a cer-

tain group, yet it can hardly be compared in emotive value to a song by one of our operatic artists. As Titchener states, when compared in pleasantness with a good dinner or the scent of a flower the color patch will seem practically indifferent. Of course results of impressions are only relative and there is perhaps sufficient emotive value in colors alone to afford pleasure when combined to form color music. However, the foregoing point is of interest in combining colors and sound music. Certainly a 'color instrument' cannot compete with a symphony orchestra, which leads to the tentative conclusion that color in such a relation should be subordinated to the role of merely providing 'atmosphere.' A 'color instrument' of definite form is conspicuous in its feebleness when in the midst of a symphony orchestra. It was suggested that the colors be used in the rendition of 'Prometheus' by combining them on the whole background of the orchestra setting without any arbitrary limits, thus providing the atmosphere. The use of diaphanous curtains, draped in loose folds and perhaps kept moving gently by electric fans placed at a considerable distance, was recommended. However, neither of these suggestions was adopted, the colors having been played on a relatively small white screen.

78. The mechanical construction of experimental apparatus for studying 'color phrases' is simple. There are two general methods of procedure which immediately occur to the experimenter. In one, the various colors composing a 'color chord' are separated physically by playing them on different parts of a white screen, thus introducing the factor of harmony and overcoming the lack of analytic ability of the visual apparatus. In the other the component colors of a color chord are mixed by superposition. Obvi-

ously, in the latter case harmony is limited to the presentation of colors successively and the predominant factor in 'composing' color music to be rendered by such an instrument would be that of color-mixture. In the former case the predominant factor would be that of the harmony of colors. In both procedures the element of rhythm and variation in brightness can be introduced. A decision regarding the mode of presenting colors — by juxtaposition or superposition — must be made before any serious attempts at composing color music can be made. Doubtless instruments employing both principles should be investigated, and with this in mind two simple instruments were constructed. One similar to that illustrated in Fig. 127 was used by Rimington, who employed arc lamps for sources of light. The various colors indicated in Table XXI were played in arbitrarily selected positions relative to each other. Obviously no purples appeared when the colors of the Rimington scale were played in this manner. This omission is inexcusable, for purple is of a definite hue and perhaps nearly as full of emotive value as any spectral color. The colors could also be mixed on a screen. A mechanical dimming apparatus was employed for controlling the brightness of the colors. Rimington evidently has experimented considerably with such an apparatus, but gives little data that supplies fundamental information from which to develop an art of mobile color. Such an instrument was constructed by the author, using tungsten incandescent lamps and fairly pure color filters, the wiring diagram being as shown in Fig. 127. Either mechanical or electrical dimmers may be used for controlling the brightness of the colors. A similar instrument was used in the rendition of the 'Luce' score

in 'Prometheus,' cited early in the present chapter. In order to overcome the arbitrariness of the relative positions at which the colors appeared upon the white reflecting screen an oscillating motion was given to the colors. By this means the colors never appeared completely superposed and appeared on various occasions on different parts of the screen.

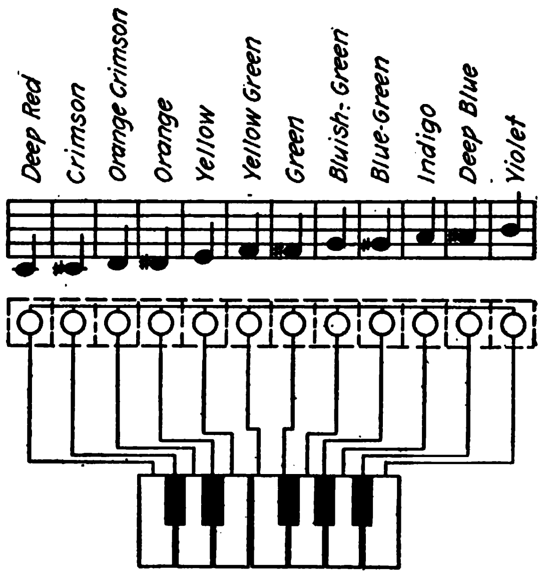

Fig. 127.—Illustrating an instrument for studying the emotive or affective value of colors and color phrases; Rimington's color code is also shown.

Another instrument constructed by the author, on the principle that any color can be matched by a mixture of three primary colors, namely red, green, and blue, is illustrated in Figs. 128 and 129. Red, green, blue, and clear tungsten lamps are respectively placed in series with specially constructed resistors. Each of the resistors, *a*, *b*, *c*, and *d*, contain ten movable contacts which are respectively connected to the corresponding keys on the keyboard. On pressing a given key the circuit is completed through the

corresponding lamps and a certain amount of resistance wire. The line voltage is applied at *V*, and *C* is a common terminal for the four circuits. The clear tungsten lamps are in reality 'daylight' lamps, thus producing white light. This light is used to dilute the colored light to any degree of saturation represented by the ten steps in intensity produced

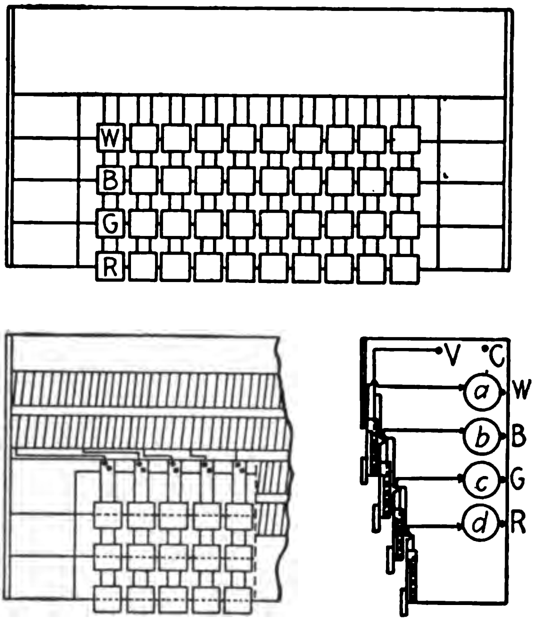

Fig. 128.—A color-mixture instrument for studying the emotive and affective value of colors and color phrases.

by pressing the corresponding keys in the upper row marked *W*. Thus ten steps in intensity can be obtained for light of each primary color and white. Such a combination is, of course, arbitrary, but is sufficiently elaborate for preliminary experimental purposes. Hundreds of different colors are obtainable, varying in brightness from that just perceptible to the maximum brightness, which is at the limit of comfortableness. The lamps are placed inside a

velvet-lined box (Fig. 129) around the rectangular aperture. The colors are mixed by superposition and viewed at present on a circular white diffusing surface placed on the back of the box opposite the viewing aperture. The movable contacts are adjusted so that any corresponding set of three keys in the *R*, *G*, and *B* rows will produce white light. Thus white light of ten degrees of brightness can be made

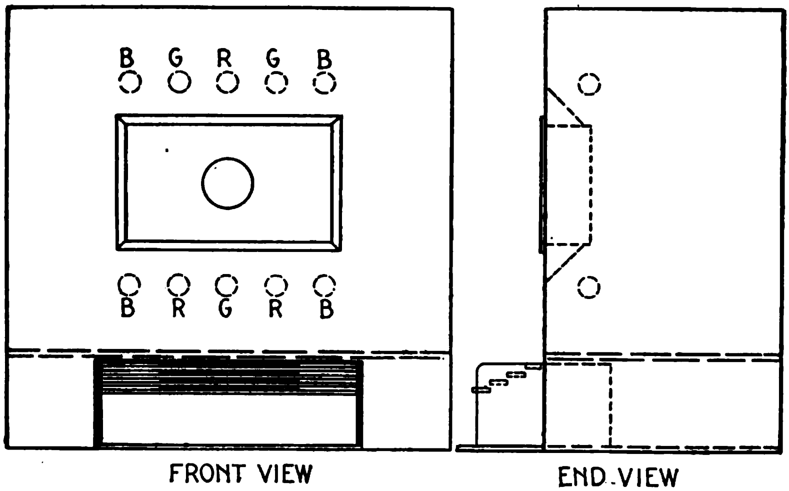

Fig. 129.—Showing the relative positions of the colored lamps in the apparatus diagrammatically shown in Fig. 128

in this manner. The upper row of keys for producing white light has been installed in order to produce greater flexibility.

Considerable personal experimenting has been done with these forms of apparatus, but little definite information has yet been derived. The foregoing has been presented to illustrate the procedure considered desirable in this work. The amount of experimenting that can be done with such apparatus is very extensive, but the first question to decide concerns the character of the data desired. Many have dreamed

of color music, some have written about it, and a few have attempted to present it. The objects of this discussion have been to show that there is no art of mobile color at present; that meager constructive data exists concerning it; that there have been hardly more than superficial attempts made to present it; that psychological studies must be relied upon to point the way toward its development; that it is a field worthy of cultivation; and that there are definite problems that must be studied in order to obtain foundation material for building up an art of mobile color.

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CHAPTER XVI

COLORED MEDIA

79. *Available Coloring Materials.* — In any kind of work a knowledge of the tools and materials available is quite important. If one may judge from the questions that are asked by many interested in various phases of color science, a brief outline of colored media and means of manipulating them should be of interest. The available coloring materials are very numerous, yet it is often difficult to find satisfactory pigments for a given purpose. It is of considerable advantage to have at hand a large variety of these materials; therefore a list of useful colored media are presented below.

Colored glasses. — Sets of samples can be obtained from various supply houses. Signal glasses afford a limited number of fairly pure colors, usually red, yellow, green, blue-green, blue, and purple.

Colored gelatines. — Very elaborate sets of colored gelatines can be obtained from theatrical supply houses. These are exceedingly useful, though lacking in permanency. If mounted between sheets of glass and kept in a ventilated position, many of them will be fairly durable. Complete sets of samples are very convenient.

Colored lacquers. — Those intended for coloring incandescent lamps are very useful, although it is often desirable to mix these carefully in order to obtain colors of greater spectral purity. Such colored lacquers vary considerably in permanency, and

wherever possible it is well to apply the coloring to sheets of glass which can be mounted at some distance from the lamp. This insures a much greater permanency.

Aniline Dyes. — For coarse work the cheap dyes used for coloring cloth will afford a fairly satisfactory range of hues. By judiciously mixing these dyes some fairly pure colors can often be obtained, although as mixing usually tends to produce muddy colors the better procedure is to have at hand a variety of fundamental pigments from which perhaps a satisfactory color can be selected. A variety of dyes of the better grade is almost indispensable for accurate color work. Such dyes are usually pure and fairly reproducible, and are the best coloring media for making photographic and other screens requiring pure colors. Sets of stains for tinting lantern slides are available. These coloring media can be purchased in various forms, liquid, powder, sheets, etc. It is probably surprising to the uninitiated what a variety of coloring materials can be obtained in the stores of a city of moderate size.

Artists' Pigments. — Such pigments are classed as pastel, water colors, and oil paints. These all have their uses in color science. Water colors are now available in opaque moist pastes, which have advantages in some classes of work.

Printers' Inks. — Such a set of pigments will be found useful by those desiring to collect a variety of coloring media. They are especially adaptable to applications similar to those found in the print shop.

Colored Papers. — The ordinary colored tissue papers are useful in demonstrating color effects, but in the study of the science of color no series is equal in purity and uniformity to the imported colored

papers, such as the Wundt colored papers supplied by Zimmerman which are mentioned in this work on various occasions.

80. *Pigments.* — As stated in #72 pigments are derived from mineral, animal, and vegetable matter, and in general the inorganic pigments are the most durable. The organic dyes are often more brilliant, and for a great many purposes are more satisfactory, than inorganic pigments, because the latter are usually more opaque. The durability of pigments is a matter of degree, and depends upon the protection provided against moisture and other destructive agents in the atmosphere, such as gases and smoke. Few pigments will withstand excessive amounts of heat and light. An extended discussion of pigments is outside the scope of this chapter, but a few details regarding common pigments should prove helpful. The chemistry of pigments obviously is complex, so no simple rules can be formulated which will always guide the colorist in making mixtures of pigments that will not interact.

Blue. — In general blue pigments reflect or transmit an appreciable amount of deep red rays, which becomes quite noticeable under ordinary artificial light. Ultramarine is considered by the artist to be a close approach to spectral blue in hue, yet it transmits a considerable proportion of red rays (Fig. 103, 122). Natural ultramarine is obtained from a mineral, but owing to its scarcity an imitation has been produced artificially in various grades. The artificial ultramarine is quite permanent and is insoluble in water, alcohol, turpentine, and oil. Ultramarine ash is a blue-gray pigment derived as a by-product in the preparation of natural ultramarine.

Cobalt-blue is readily prepared quite pure and is

very durable, although it is far from a pure blue. Its reddish appearance under artificial light indicates that it reflects a large proportion of deep red rays, which conclusion is supported on analyzing the reflected light (see *b*, Fig, 122). Smalte is a powdered cobalt glass of a brilliant, transparent color that is quite durable.

Prussian blue, like most artificial pigments, varies in quality. It is not generally as durable as the preceding blue pigments, but is fairly permanent if used alone. It interacts with many pigments. In oxalic acid it forms a satisfactory writing fluid. It can be made by mixing a ferric salt with potassium ferrocyanide. It can be deposited intimately in contact with a fabric if the latter be dipped first into one solution and then into the other. An excess of the potassium ferrocyanide forms a compound known as soluble prussian blue.

Indigo is derived from the vegetable kingdom and belongs to the lakes. It is insoluble in water, ether, oils, and cold alcohol. It dissolves in boiling concentrated alcohol and fuming sulphuric acid. In the latter solvent it forms saxon blue.

There are numerous blue aniline dyes, but most of them transmit red rays as well as blue.

Green. — Chromium oxide is a durable, opaque, deep green pigment.

Emerald-green usually is a carbonate of copper mixed with alumina. It is quite opaque and durable and of a brilliant green color.

Many greens are made by mixtures of such pigments as chrome-yellow and prussian blue, but the luminosity of such a mixture depends upon the amounts of green in the two pigments (# 72).

Terra verte, a native mineral found in various

parts of Europe, is opaque and durable and quite satisfactory in color.

Malachite green is a natural carbonate of copper. It is pale green in color and moderately permanent. This pigment is being imitated artificially.

There are several beautiful greens among the organic dyes, but of less durability.

Yellow. — Gamboge closely represents spectral yellow. It is a gum resin employed very extensively in water colors. It is a bright, transparent, permanent yellow.

Cadmium-yellow is a brilliant, opaque pigment which forms fairly satisfactory greens by mixing with a number of the greenish blue pigments. It contains sulphur, and therefore should not be mixed with pigments containing lead. It is satisfactory in combination with zinc-white.

Indian yellow is a permanent, fairly transparent, orange-yellow. The pure pigment burns easily, which is a means of detecting fraudulent adulteration or substitution.

Chrome-yellow is lead chromate and varies in color from a lemon-yellow to a deep orange, depending upon the chemical constitution and the admixture of other substances. It is used in both oil and water colors.

Zinc chromate is an opaque, permanent yellow pigment which mixes well with other pigments.

Potassium bichromate is a permanent yellow having many uses. It dissolves in water and appears a greenish yellow in slight concentration, but approaches a deep amber in a saturated solution.

Satisfactory spectral yellows are rare, even among the large number of organic dyes available. Tartrazine, aurantia, martius-yellow, and naphthol-yellow

are representative of these dyes. They have a greenish tinge.

The ochres, which are earthy combinations of iron oxides, yield several yellow pigments. The native ochres are yellow and red.

Red. — Carmine, which is obtained from the cochineal insect, closely imitates spectral red, and is considered by many as the most beautiful red pigment known. It is opaque and mixes well with other pigments but is not very permanent.

Vermilion is a natural compound of sulphur and mercury found in many places, and in mineralogy is called cinnabar. It is available in several hues, varying from orange-red to deep red in both oil and water colors.

Indian red and venetian red are native ochres. Some of the yellow ochres are converted into light red pigments by calcining.

The madder pigments, which are lakes, include various reds. The coloring matter is extracted from roots and united with alumina. These pigments are not very permanent.

Lakes. — The coloring elements used in lakes are generally of vegetable origin. These possess the property of being precipitated from an aqueous solution by metallic oxides, with which they combine. They have alumina, and sometimes other oxides associated with them, for a base to give them body. If it were not for the affinity of these oxides for many organic coloring matters many colors would not be available. For example, indian lake contains a coloring matter extracted from lac; the coloring element in yellow lake is derived from berries; and the coloring matters in cochineal and madder are extracted as described above.

White. — White pigments are used in diluting colored pigments for obtaining tints.

White lead is carbonate of lead. It has many commercial names, but perhaps flake white is the most common. It is a very opaque pigment. Oil gives it a yellowish tint and should not be used very freely when a pure white surface is desired. White lead is attacked by sulphur and converted into black lead sulphide. It is more liable to react with other pigments than zinc-white, which is a formidable rival.

Zinc-white is oxide of zinc. It possesses all of the good qualities of white lead and perhaps none of the objectionable features. It is claimed that the covering power of zinc-white is greater than that of white lead. Its sulphide is white, so that sulphur does not discolor it.

Black. — Black pigments are usually carbons. Ivory-black is obtained from ivory waste and possesses a rich black appearance. It produces excellent grays when mixed with white. Bone-black is a cheaper substitute.

Lamp-black is obtained by burning certain substances in an atmosphere containing little air or oxygen. Kerosene and coal gas yield soot which makes a satisfactory black.

Nigrosine is a black pigment, soluble in water, which is very useful. It can be readily incorporated into various mediums and makes a fairly satisfactory neutral tint screen in a gelatine film.

81. *Solvents.* — In making lacquers various solvents are available, the properties of some of them being given below. (See Table III.)

Methyl alcohol (wood alcohol) mixes with water in all proportions. It is similar to grain alcohol as a solvent.

Ethyl alcohol (grain alcohol) dissolves many resins, oils, soaps, glycerol, camphor, celluloid, phenol, iodine, and many chlorides, iodides, bromides, and acetates.

Acetone dissolves fats, oils, gums, resins, celluloid, and camphor, and mixes in ethyl alcohol and water.

Ether, produced by distilling alcohol and sulphuric acid in proper proportions, dissolves fats, oils, resins, iodine, bromine, and many alkaloids. It mixes with alcohol, benzine, chloroform, and slightly with water.

Amyl alcohol mixes with benzol, ether, alcohol, and slightly with water. It dissolves oils, camphor, resins, alkaloids, and iodine.

Amyl acetate (artificial banana oil) mixes in all proportions with alcohol, amyl alcohol, and ether. It dissolves celluloid and is used in the preparation of collodion varnishes.

Benzine should not be confused with benzene or benzol, the latter being derived from coal tar. It is a substitute for turpentine in paints, oils, and driers.

Glacial acetic acid (pure acetic acid) mixes with water, alcohol, and ether. It dissolves oils, phenols, resins, and gelatine.

Linseed oil is used as a vehicle in oil pigments. It dissolves hard resins, amber, and copal and is used for making varnishes.

Poppy oil replaces linseed oil in oil pigments where the yellow color of the linseed oil is objectionable.

Benzene is derived from coal tar. It mixes with alcohol, ether, petrolic ether, turpentine, and dissolves oils, fats, waxes, iodine, and rubber. It loosens paint. Benzol is an impure benzene. Toluol, toluene, and methyl-benzol are similar to it.

Gelatine is soluble in hot water and concentrated acetic acid, forming, in the latter case, an adhesive

paste. Potassium bichromate renders it insoluble on exposure to light. Formalin added to a warm aqueous solution and permitted to dry renders the gelatine insoluble in hot water.

Turpentine dissolves fats, oils, and resins. It is used for thinning paints and varnishes.

Venice turpentine is slowly soluble in absolute alcohol, but is readily soluble in ether, acetone, petrolic ether, benzol, and glacial acetic acid. It is used in fixing colors, in printing inks, and in spirit varnishes to give elasticity.

Canada balsam is soluble in ether, chloroform, petrolic ether, benzol, turpentine, and gasoline. It is used to cement glasses, and owing to the fact that its refractive index is close to that of glass it practically eliminates reflection and refraction of light at the surfaces in contact with it. For this reason it is excellent for cementing cover glasses on color filters.

82. *Varnishes.* — A varnish is usually made by dissolving a resin in a medium such as alcohol, turpentine, or oil, the first forming a spirit varnish, the second a turpentine varnish, and the third an oil varnish. The so-called resins most commonly employed are copal, sandarac, mastic, dammar, shellac, and amber. The properties of a varnish depend largely upon the resin and somewhat upon the solvent. If the solvent is volatile, like alcohol and turpentine, after the varnish dries the resin is left in the same state as before it was dissolved. These are quick drying varnishes. If the solvent be an oil, then both the oil and resin remain and the coating after drying is pliable and tough.

Copal is soluble in hot linseed oil; sandarac in alcohol; mastic in ether, in hot alcohol, and in tur-

pentine; dammar in alcohol and in turpentine; shellac in alcohol and in a solution of borax; amber in boiling linseed oil; gum arabic in water forming a varnish for water colors; gum kauri in hot ether, in turpentine, in amyl alcohol, and in benzol; common resin in ether, alcohol, turpentine, benzol, acetone, or hot linseed oil.

Common resin in wood alcohol forms a cheap varnish. An excellent spirit varnish is obtained by dissolving dammar in alcohol and turpentine, the proportions of the latter being respectively about four to one. A weather-proof varnish can be made of dried copal 7%, alcohol 15%, ether 77%, and turpentine 1%.

83. *Lacquers.* — Shellac dissolved in alcohol and decanted after settling provides a cheap lacquer and solvent for some aniline dyes. Ordinary shellac is quite yellowish in color, so that the use of bleached shellac is sometimes advisable. The latter, however, does not dissolve as readily as the yellow shellac, but satisfactory proportions are one part of bleached shellac to eight parts of 90% alcohol. In making colored lacquers the aniline dyes are usually more satisfactory on account of their transparency, although they lack permanency when exposed to radiant energy. The inorganic pigments are more opaque, but are usually more permanent. In general they do not dissolve, although they can be held in suspension. They are not as generally satisfactory as the aniline dyes for coloring media, excepting for their greater permanency.

Photographers' ordinary collodion, which consists of pyroxylin (soluble guncotton) dissolved in ether and alcohol, can be used as a solvent for aniline dyes for coloring incandescent lamp bulbs.

Ordinary photographic film (from which the emulsion has been removed) dissolved in amyl acetate, alcohol, or acetone, provides a satisfactory lacquer for lamp colorings. Ordinary clear celluloid scraps containing a large percentage of camphor are readily dissolved in acetone, thus providing a cheap lacquer for dyeing purposes. The latter celluloid scraps dissolve in wood alcohol and in amyl acetate, but when the lacquer drys it becomes white; however, this provides a means of making a cheap though not very satisfactory opal lacquer. Ordinary white celluloid scraps dissolved in wood alcohol provide a very cheap opal lacquer. A permanent opal solution can be made by mixing pure zinc-white to a fair consistency, using but little oil with a few drops of gold size. This can be applied by stippling with a flat-headed brush. Obviously this solution can be readily colored by mineral pigments, but such mixtures are not very transparent.

If it is desirable to make a transparent glass diffusing or translucent, a saturated solution of epsom salts in warm water is satisfactory. After applying this solution and permitting it to dry, a surface is obtained similar to that produced by etching or sand blasting. This can be colored with some of the dyes soluble in water. Such a surface is not permanent.

84. *Dyeing Gelatine Films.* — Perhaps the most convenient manner of making color filters for a large variety of uses is in applying the coloring matter to gelatine. A simple scheme is found in placing a photographic plate in an ordinary fixing solution for a few moments, and, after thoroughly washing it, permitting it to soak in an aqueous solution of the dye. The gelatine coating will absorb considerable of the dye, the depth of coloring being controlled chiefly by

the concentration of the colored solution and somewhat by the period of time the plate is permitted to remain in the bath. If the coloring is too dense, some of it can be washed out by placing the plate in running cold water. It is sometimes necessary to acidulate the solution slightly or to add ammonia, alcohol, etc., in order completely to dissolve the dyes, but this does not usually interfere with the above process.

Better control is obtained by adding an aqueous solution of the dye to a solution of gelatine in warm water and flowing the dyed gelatine on a level plate of glass or other transparent media. This procedure lends itself to accurate reproduction. It is advisable to use a harder variety of gelatine, which can be purchased from chemical supply houses. From four to six per cent of gelatine (by weight) in water is found satisfactory. The gelatine is permitted to soak in cold water for an hour or more; then the vessel containing it is placed in a basin of water and gently heated. It is advisable not to heat the water above 50 deg. C or more than is necessary to liquefy the gelatine. This solution should be filtered through a coarse cloth free from lint, and the plate should be flowed in a dust-free atmosphere. Sometimes it is well to warm the glass plate before flowing the gelatine. The amount of gelatine solution should be approximately one cubic centimeter to ten square centimeters of area. It is well to permit the plate to dry uniformly until completely hardened. The surface will not be optically plane, but where this is necessary another plate glass may be cemented on top of it with Canada balsam and a moderate pressure should be applied for several days. When dried at a temperature of 40 deg. C, only a day or two is required for the balsam to harden. After the plates

are thoroughly dry they can be bound together at the edges with metal strips or gummed paper. A drying cabinet heated by means of carbon incandescent lamps is very safe and convenient, and the temperature can be readily regulated by varying the number of lamps in operation.

Gelatine sheets can be made by flowing the gelatine solution upon a level aluminum plate, from which they are readily removed after drying. Doubtless there are better processes for the latter procedure used in the manufacture of such sheets.

85. *Celluloid.*—This material is of interest because of its use in lacquers and its transparency and durability, which make it a substitute for glass or gelatine films. An undesirable characteristic, however, is its inflammability, although tests indicate that the commercial celluloid is not dangerously explosive. It resists most acids and bases of moderate concentration when cold. Glacial acetic acid rapidly dissolves it, and when this solution is poured into water the nitrocellulose, camphor, and other substances are precipitated. It dissolves in alcohol, the best solvent being camphorated alcohol (10 parts camphor to 100 parts alcohol). Acetone, either the liquid or vapor, dissolves it. Celluloid films can be made by casting or by a continuous process, and can be polished by felt disks or rollers, using powdered pumice stone, soap, or polishing oil.

Celluloid takes up dye very well from a solution of the coloring in alcohol. The colors for staining should act like mordants, or their application should be similar; that is they should penetrate deeply into celluloid, thus coloring the mass. The usual solvents are alcohol, acetone, acetic acid, and amyl acetate.

In staining celluloid it is first moistened by a softening agent in which the aniline dyes are mixed; then on dipping the celluloid into such a solution the dye penetrates the mass.

Celluloid is readily colored by the foregoing methods, but can also be colored by means of mineral dyes, though if transparency is desired, which is the condition considered most important here, these colorings are not as satisfactory, although they provide permanent colors. A solution of indigo in sulphuric acid and neutralized by potassium hydroxide produces a blue dye. Another method which furnishes a more satisfactory blue results in the production of Prussian blue. The celluloid is immersed in a bath of ferric chloride, and after drying is dipped into a bath of potassium ferrocyanide. To color celluloid green, it is dipped into a solution of verdigris and ammonium chloride. To color it yellow it is immersed in a solution of lead nitrate and then dipped into a solution of neutral potassium chromate. Solutions of chrysoidine, auramine, and many aniline dyes in alcohol are satisfactory. To color celluloid red it may be dipped first in a dilute solution of nitric acid, then immersed in an ammoniacal solution of carmine. Color will be readily absorbed by celluloid if its surface is first sandblasted.

86. *Phosphorescent materials.* — A variety of phosphorescent materials are available from chemical supply houses in varying degrees of purity and of various colors. These have their place in colored effects, especially for demonstration purposes. They have been used in theatrical productions, but the greatest drawback is the difficulty of obtaining an illuminant emitting rays of short wave-lengths (which are the most effective in exciting phosphorescence)

in sufficient intensities. The bare carbon arc and the quartz mercury arc are the most intense excitants for this purpose among artificial light sources. Luminous calcium sulphide, sometimes known as Balmain's paint, is cheap and active and emits phosphorescent light of fairly long duration. It forms the basis of several cheap though not highly satisfactory phosphorescent paints.

Phosphorescent oil paints can be made by using pure linseed oil instead of the varnish which is ordinarily used in phosphorescent paints. For artists' paints the varnish should be replaced by pure poppy oil. Phosphorescent material can be applied to cloth and paper by omitting the varnish, mixing the powder in water, and applying this paste in a convenient manner. For applying to glass or porcelain, the varnish is replaced by Japanese wax in a slightly greater quantity, and olive oil is added. These mixtures can be fired successfully when air is excluded. Water glass (sodium silicate) is a satisfactory protecting agent for such applications.

87. *Miscellaneous Notes.* — For purely decorative effects of a temporary nature some of the colored metallic salts that crystallize when the solvent is evaporated are quite useful. For instance, if a saturated solution of potassium bichromate be added to a rather concentrated aqueous solution of gelatine, and this mixture be flowed while hot upon a level plate glass, on cooling it forms a yellow diffusing filter of crystalline structure. Such screens do not have a wide application; nevertheless they can be used for temporary decorative purposes. A weak solution of potassium bichromate can be used in gelatine without crystallizing or drying. The greenish tinge of this yellow can be overcome, if desirable,

by an addition of a slight quantity of a dilute solution of a red or pink dye.

The air brush is a useful instrument for the application of liquid colorings, especially when the pigments do not readily dissolve in lacquers. Lamps and other objects can be readily colored by immersion in a colored lacquer, but this is not a very satisfactory procedure when the coloring matter is merely held in suspension. By means of an air brush any colored solution can be readily applied to an object with a fair degree of uniformity. Perhaps the most discouraging factor in the production of colored lighting effects is the lack of permanent blue and blue-green pigments that will readily dissolve in a satisfactory lacquer. Prussian blue and cobalt-blue are quite permanent, but insoluble in common lacquers. These can be successfully applied by means of an air brush when they are held in suspension in a lacquer of thin varnish. By occasionally diverting the flow of air through the liquid such insoluble pigments can be kept in suspension in the binding solution. For this class of work a small motor operated from two or three dry cells or a small transformer and equipped with a vertical stirring rod is exceedingly useful.

Pigments can be readily tested for durability by placing them on strips of glass and partially covering them with glass. These should be exposed to sunlight or to the radiation from an arc lamp, keeping part of the pigment covered. The exposed portions should include both the unprotected portion and that protected by the cover glass. Another convenient method, depending of course upon the final uses to which the pigments or lacquers are to be put, is found in applying them directly to incandescent lamp bulbs.

The lamps should be dyed in pairs, and one should be preserved while the other be operated on normal or slightly above normal voltage. If the pigments are eventually to be exposed to the weather, the tests should be made out of doors.

These are a few data that have arisen in experimental work in the study and application of the science of color and in the production of various color effects which may prove helpful to those interested in color. See next chapter.

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CHAPTER XVII

CERTAIN PHYSICAL ASPECTS AND DATA

88. A perusal of the literature on colored media and a general acquaintance with color industries has led to the conclusion that the chemistry of such substances greatly dominates the physics in color-technology. In fact, much of the physics of color is so little used in some of these activities that it is either not generally understood by color-technologists or its value is underestimated. Spectral analyses — the quantitative determinations of the spectral characteristics of colored materials — provide the foundations for many important aspects of color-technology and without such data some work is conducted more or less blindly. With such data and those derived from less analytical methods, many interesting facts of color-technology can be bared and various factors can be determined which are unapproachable from the viewpoint of chemistry or from ordinary visual inspection.

Of the various methods of analyzing color, that of the spectrophotometer is the most analytical and it provides data of far greater usefulness in the physics of color than the data which are yielded by any of the other methods. By this method the reflection- (or transmission-) factors of the coloring media are determined for radiant energy of all wave-lengths in the visible spectrum. When these are plotted we have the spectral reflection (or transmission) curves for the visible spectrum. By the same method the spectral character of an illuminant may be obtained. By multi-

plying the relative energy-values of the various wave-lengths of any illuminant by the corresponding visibilities of radiation, the spectral luminosity-distribution curves are obtained for the given illuminant. These latter will vary with the illuminant and are often of greater importance than the spectral energy-distribution curves from a visual viewpoint. It is obvious that by multiplying corresponding spectral values, the spectral energy-distribution and luminosity-distribution curves of any colored medium may be readily obtained for any illuminant. Such data and their uses will be presented later.

Owing to the indefiniteness and limitations of the data yielded by most of these so-called colorimetric methods and the difficulties attending the use of the monochromatic colorimeter at present, this chapter will be confined almost entirely to spectrophotometric data and their uses. Many instances arise when the degree of absorption for ultra-violet and infra-red rays is of interest. The former can be determined readily by spectrophotography and the latter by means of such energy-measuring instruments as the bolometer or thermopile.

89. *Types of Colored Media.* — Three classes of colored media will be represented and discussed, namely, pigments, dyes, and vitrifiable colors or colored glasses. Pigments are distinguished from dyes by their insolubility in their vehicle, while dyes are soluble. This distinction may appear arbitrary, especially in some cases, however, it is employed to some extent and is a convenient classification. Pigments may be distinguished from paints in that the latter are pigments in a vehicle or medium. Vitrifiable colors are those which impart color to glass and to similar substances. Among pigments are found two general classes; one in which each particle is homogeneous and the other in which

a colorless base has been colored by depositing coloring matter upon it. Colored media vary in many physical characteristics such as opacity, fineness, and refractive-index, and they may be considered as varying in 'coloring power.'

The color of a pigment in a finely divided state, whether the particles are separated by air or by a vehicle, is due to innumerable selective reflections from, and transmissions through, the minute particles. If the powdered pigment is given a smooth surface by pressure it does not appear as pure in color as when it is loosely packed because in the latter case a greater proportion of the incident radiant energy is able to penetrate more deeply into the body and becomes colored by selective reflections and transmissions. Radiant energy is regularly reflected from even the small surfaces of the particles of pigment and in those cases where the minute areas of surface are properly oriented, this regularly reflected light does not find its way further into the pigment but is reflected practically unaltered in spectral character as compared to that energy which penetrates further into the mass. Thus, there is always reflected from pigments some radiant energy which is practically unchanged in spectral character which accounts partly for the general lack of purity of the colors of pigments. It is seen that the character of the surface is important. Furthermore, the refractive-indices of the pigment and of the vehicle (air in the case of dry powders) are of importance because the amount of light regularly reflected from a surface is dependent upon these refractive-indices. A careful study of the influence of the vehicle upon the color of a paint leads to interesting data from this viewpoint alone.

Careful observation will reveal the influence of the porosity of a pigment-surface upon its color. An excel-

lent example for the purpose of illustration here is the color of a white cotton fabric compared with that of a white silk fabric after both have been soaked in the same dye-solution. In Fig. 130 are shown reproductions of microphotographs of white cotton and silk fabrics as photographed against a black background. It is seen that the silk is more transparent than the cotton fibers; in fact, the cotton fibers are merely translucent as compared with the transparency of silk fibers. The latter permit the radiant energy to penetrate more deeply, in general, than the cotton fibers; in other words, the cotton fibers by diffuse reflection turn the energy backward before it has penetrated very deeply. For this reason the silk fabric appears of a purer color compared with that of the cotton fabric dyed in the same solution, the result, in the case of the silk, being similar to that which would have been obtained with the cotton if the latter had been dyed in a more concentrated solution of the dye.

In a manner similar to the case of pigments the solvent appears to have certain influences upon the color of a solution of a dye although this subject has not been thoroughly studied. The substance upon which a dye has been deposited by immersion is also of importance in spectral analysis as is indicated by the case of dyeing cotton and silk fibers, Fig. 130. The transmission-factor of a dye-solution is a simple logarithmic function of the depth of a given solution or of its concentration, but this relation varies with the wave-length, in general in no definite relation between wave-length and spectral transmission-factor. For this reason no simple relation between total transmission and depth or concentration can be established. Such values of total transmission must be determined by direct measurement or by integration, as will be discussed later.

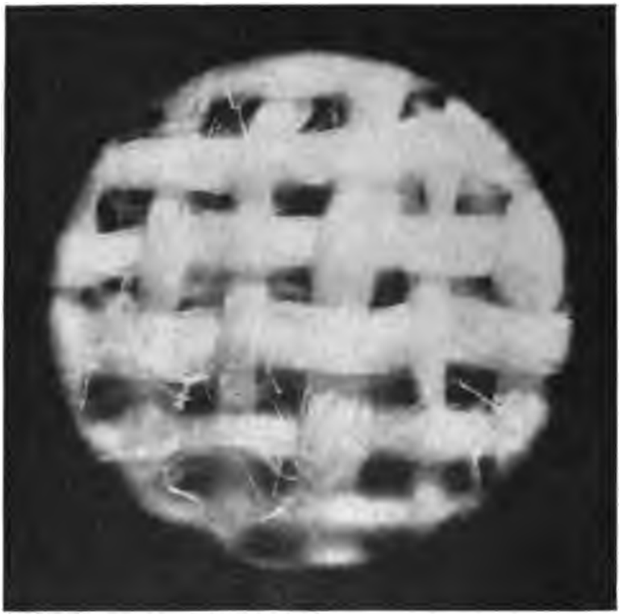

Fig. 130. — Cotton.

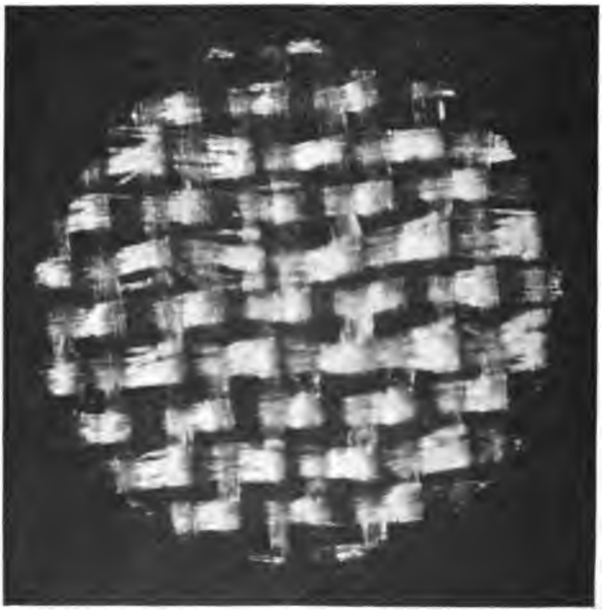

Fig. 130. — Silk.

Colored glasses can be treated much in the same manner as dye-solutions. A given concentration of coloring material in a glass, that is, a given colored glass, apparently obeys the same law relating thickness and transmission-factor for a given wave-length as a dye-solution. However, it is not established that the introduction of various amounts of the coloring material (generally metallic oxides) results in corresponding concentration as would be true in the case of dyes. In glass there is more or less chemical action and the uncertain conditions of melting make this point difficult to decide.

The physics of the process by which glasses are colored by means of metallic compounds is not wholly clear. There are many chemical analogies which are of interest for their parallelism to the colors imparted to glasses by the metals in different states but the reasons for the appearance of the colors cannot be considered as being thoroughly established. Garnett[1] has presented a very interesting discussion of the colors exhibited by certain glasses in which metallic oxides had been incorporated. It is a common supposition that the colors of certain glasses, such as gold red glasses, are due to the presence of very minute particles of metal. Solutions of some metals exhibit colors which are often exhibited by colored glasses in which the same metals have been introduced. Siedentopf and Szigmondy, by powerfully illuminating specimens of colored glass and colored colloidal solutions of metals obliquely, or at right-angles to the line of sight, were able to detect the presence of the metallic particles. Garnett's work explained some of their observations.

It is commonly considered that metals color glass in two ways, one by being in a state of true solution in the glass and the other by being in a colloidal state.

An example of the former is copper blue-green glass and of the latter, gold red glass.

In dealing with the physics of colored media from the viewpoint of the physicist, one cannot avoid the conclusion that there is a wide application of physics to color-technology in many directions quite unexplored.

90. *Pigments.* — In presenting data which it is hoped will be of direct use to others, only those colored media have been selected which are thought to be fairly constant in composition and representative. The spectral reflection-factors of a group of dry powdered pigments, commonly used in the paint industries and which from general observation appear representative, were determined by means of the spectrophotometer and the data are presented in Table XXII. The light was reflected from a thick layer of the powder, the surface being gently smoothed by means of a sheet of plane glass. Whites and blacks have been omitted but these are by no means always neutral pigments. Whites are very commonly yellowish and blacks (which are only approximately black, varying in reflection-factor from 0.02 to 0.1) are often bluish or reddish. Although these departures from neutrality are not relatively great they are sufficient to be detected by means of the spectrophotometer. Such small departures are readily detected by painting the inner surface of a box with such a supposedly neutral pigment and by viewing a white surface indirectly lighted by means of a light-source inside the box. The visible radiation suffers innumerable reflections (see # 65) from the walls of the box and that which illuminates the white surface is therefore much more colored than the pigment would appear under direct illumination. The spectral reflection-factors of pigments are more difficult to obtain than the transmission-factors of dyes in solution because in the former case

TABLE XXII

Spectral Reflection-factors of Thick Layers of Dry Powdered Pigments

	0.44μ	0.46μ	0.48μ	0.50μ	0.52μ	0.54μ	0.56μ	0.58μ	0.60μ	0.62μ	0.64μ	0.66μ	0.68μ	0.70μ
American vermilion	0.08	.06	.05	.05	.06	.06	.09	.11	.24	.39	.53	.61	.66	.65
Venetian red	.05	.05	.05	.05	.05	.06	.07	.12	.19	.24	.28	.30	.32	.32
Tuscan red	.07	.07	.07	.08	.08	.08	.08	.12	.16	.18	.20	.22	.23	.24
Indian red	.08	.07	.07	.07	.07	.07	.07	.11	.15	.18	.20	.22	.23	.24
Burnt sienna	.04	.04	.04	.04	.05	.06	.09	.14	.18	.20	.21	.23	.24	.25
Raw sienna	.12	.13	.13	.13	.18	.26	.35	.43	.46	.46	.45	.44	.45	.43
Golden ochre	.22	.22	.23	.27	.40	.53	.63	.71	.75	.74	.73	.73	.73	.72
Chrome yellow ochre	.08	.09	.07	.07	.10	.19	.30	.46	.60	.62	.66	.82	.81	.80
Yellow ochre	.20	.20	.21	.24	.32	.42	.53	.63	.64	.61	.60	.59	.59	.59
Chrome yellow (med.)	.05	.05	.06	.08	.18	.48	.66	.75	.78	.79	.81	.81	.81	.81
Chrome yellow (light)	.13	.13	.18	.30	.56	.82	.88	.89	.90	.89	.88	.87	.85	.84
Chrome green (light)	.10	.10	.14	.23	.26	.23	.20	.17	.14	.11	.09	.08	.07	.06
Chrome green (med.)	.07	.07	.10	.21	.21	.17	.13	.11	.09	.07	.06	.06	.06	.05
Cobalt blue	.59	.58	.49	.35	.23	.15	.11	.10	.10	.10	.11	.15	.20	.25
Ultramarine blue	.67	.54	.38	.21	.10	.06	.04	.03	.03	.04	.05	.07	.10	.17

more or less energy is regularly reflected from the particles directly into the instrument. Care must be taken to avoid placing the pigment surface in such a position with respect to the slit of the instrument and to the light-source that an undue amount of regularly reflected visible radiation enters the instrument. The visible radiation which is thus regularly reflected is

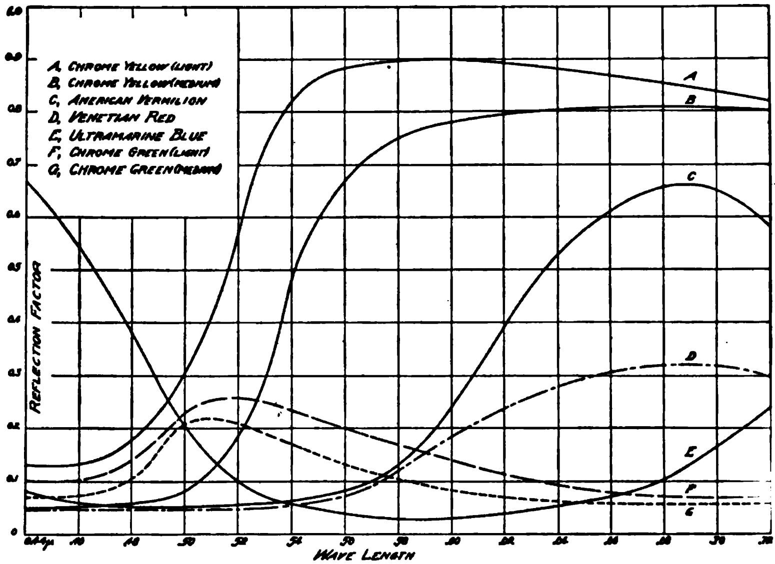

Fig. 131. — Pigments.

practically unchanged in spectral character as compared with that which penetrates into the interstices of the pigment and is colored by innumerable transmissions through, and reflections from, the minute particles of pigment. At any angle some of the energy is regularly reflected from the minute portions of the surfaces of the particles which are properly oriented. This accounts partly for the general lack of purity of the colors of 'opaque' pigments. The data of Table XXII are plotted in Figs. 131 and 132.

Spectral analyses in the ultra-violet and infra-red

regions are often of interest in general color-technology. In the former case spectrophotography is the simplest method of attack although the procedure is a tedious one if high accuracy is desired. It is necessary to establish photographic density and pigment-illumination (or exposure) relations for various wave-lengths in order to obtain the reflection-factors for radiant energy of

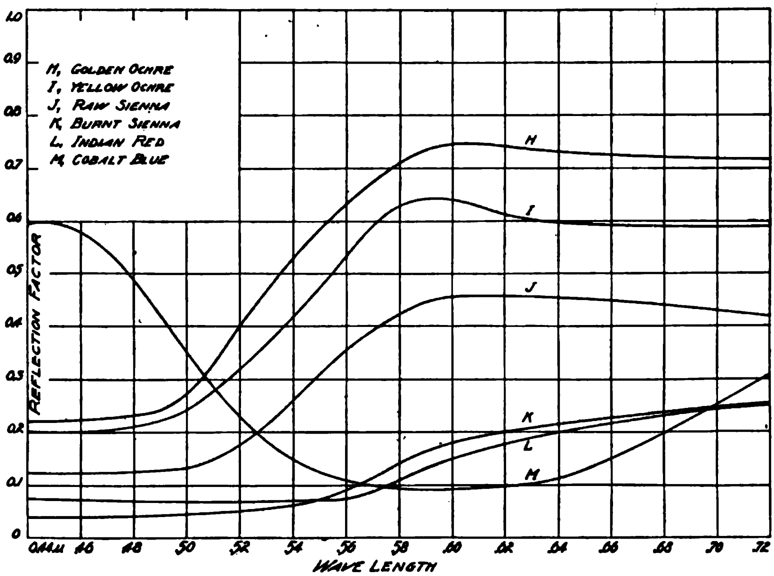

Fig. 132. — Pigments.

various wave-lengths. Besides this the ordinary precautions of photographic procedure must be taken. Another possible method is that which involves the use of the photo-electric cell. No systematic data on pigments in the ultra-violet region have been obtained so none will be presented, although ofttimes it has been necessary to investigate this region for a particular pigment. It is well to recognize the importance of such analyses in cases involving ultra-violet light. An excellent example is zinc white which absorbs ultra-violet energy quite freely.

The investigation of the infra-red region requires a more elaborate apparatus although in many cases where total energy-absorption is of interest this can be obtained rather easily by means of the thermopile or bolometer. In fact, the ordinary radiometer or even the thermometer covered with a pigment yields data which have some uses in practice. Coblentz[2] has published interesting data on the reflection-factors of various substances for infra-red and visible radiation of several wave-lengths. Among the substances which he studied were a number of pigments. The reflection-factors of white pigments for energy of wave-lengths 4.4μ varied from about 0.1 to 0.4 and at 8.8μ and 24μ were considerably lower. These data especially emphasize the localized nature of absorption-bands as, for example, cobalt oxide is a better reflector of long-wave energy than zinc oxide, yet for visible rays it possesses an extremely lower reflection-factor than zinc oxide. Lead oxide is a much more efficient reflector of long-wave energy than zinc oxide, magnesium carbonate and other white pigments. The importance of the infra-red analyses is apparent in many practical activities. Coblentz has pointed out that a pigment which has a low reflection-factor for energy of wave-lengths in the region of 8μ to 9μ is a better house paint in hot climes because it re-radiates maximally in this region where the maximum radiation from bodies of temperatures from 20° to 25° C. is found. If the paint has a high reflection-factor for visible rays it thus minimizes the heating effect of the incident energy. Such a combination is quite desirable in minimizing the heating effect of solar rays. This is merely one example of a vast number of interesting problems which could be met with more intelligence if spectral analyses were available.

91. *Some Optical Properties of Pigments.* — In con-

sidering the optical properties of a painted surface it is necessary to distinguish between a pigment and a paint. The former and its vehicle constitute the paint and the optical properties of a painted surface depend not only upon those of the pigment but also upon the vehicle and the surface covered. H. E. Merwin[3] has made interesting studies of these properties.

Most pigments, with the exception of lakes, consist of minute crystals and the color commonly varies with the direction of the passage of light through a crystal. Therefore, the shape of these crystals influences the value of a pigment. The transmission- (and absorption-) bands of pigment crystals are rather wide and shallow and small grains are more transparent than large ones of the same material. For this reason, a pigment consisting of small grains is generally brighter than one of large grains. Small grains may be considered to have diameters of the order of magnitude of 1μ and large ones of the order of 10μ. Usually the diameter of grains of colored pigments lies between 0.5μ and 10μ.

The coloring power of a pigment generally increases as the size of the grain decreases but there is no definite relation covering different substances. For a given amount of pigment it is obvious that the total amount of surface exposed to intercept light increases inversely as the square of the diameter of the grains, although the ability of a grain to alter transmitted light in any direction increases more slowly than the diameter.

Merwin considered four classes of colored pigments with regard to their adaptability to the making of tints and shades. They are as follows:

a. Colored grains are chiefly of such size that if closely packed in a single layer they would transmit (or diffuse and transmit) a clear tint (say roughly 40 to 60 per cent. white). From 5 to 20 such layers would

produce a full color. Either clear tints or pure shades can be made from such a pigment. Examples: chrome orange, chrome yellow, verdigris, ultramarine blue.

b. Grains are so transparent that white light after traversing many layers of grains still contains a good deal (20 per cent. or more) white. Such a pigment can be used in making clear tints but not pure shades. Examples: barium yellow, basic copper carbonate, strontium yellow.

c. A single layer of grains absorbs several per cent. of the characteristic hue, and other hues almost completely. Pure shades and dull tints may be made from such a pigment. Examples: vermilion, scarlet chromate, Harrison red, chrome green.

d. Single grains absorb several per cent. of the characteristic hue and even several layers of grains do not absorb other hues completely. When darkened by a black pigment dull shades result, and when lightened by a white pigment dull tints are formed. Examples: Naples yellow, some Dutch pinks and yellow ochres.

In the last two classes diffusing power determines to some extent and absorbing power to a greater extent, what range of pure shades can be obtained.

Vehicles when dried have refractive-indices in the neighborhood of 1.5 and this indicates that the amount of light regularly reflected from a smooth surface of a vehicle is about four per cent. A substance to be most effective as a pigment should have a high refractive-index for the hue it most freely transmits. The refractive-index varies considerably in the neighborhood of an absorption-band, being greater on the long-wave side than on the short-wave side. This is a reason for the greater refractive-indices usually exhibited by yellow, orange, and red pigments than by blue and violet. Of course, the refractive-index of a lake is largely deter-

mined by the base and is usually comparatively low. If the refractive-index of a pigment closely matches that of the vehicle, the former will diffuse very little light. Such a pigment would ordinarily be mixed with one of higher refractive-index which will diffuse the light.

Obviously, a black pigment to appear black in a dried vehicle should have the same refractive-index as that of the vehicle and it must absorb all the light incident upon it. In the dry state surrounded by air the pigment particles will reflect some light regardless of their absorbing power. Even when the refractive-indices of pigment and vehicle are equal, there is reflected directly from the surface of the paint about 4 per cent. of the incident light. To overcome this, light-traps such as possessed by a velvet may be provided. Ivory black is an excellent black because its refractive-index is nearly the same as that of oil or varnish.

From the foregoing consideration it is obvious that a high refractive-index is essential to a white pigment. The grains should be fine and there should be no selective scattering of light of various wave-lengths. The burning vapor of metallic zinc produces very fine grains of zinc oxide. These are less than 1μ in diameter. Most of the zinc oxides contain enough fine grains less than 1μ in diameter to give a bluish tint to paints by virtue of the selective scattering of light of the shorter wave-lengths.

92. *Some Applications of Spectral Analyses of Pigments.* — The chief use of data derived from such spectral analyses is that of establishing the spectral character of the pigment. The general value of such data needs no defense, for it is the actual foundation of the pigment as a coloring material. Its purity is thus established; its influence in color-mixture may be predicted;

the purity or desirability of a color resulting from various mixtures of pigments whose spectral analyses are available may be predetermined; and in many ways such data are useful. It is quite beyond the scope of a single chapter to discuss all the physical uses of such data, besides it is the intention to confine the discussion chiefly to aspects which are likely to be less commonly appreciated. For the latter purposes other data such as the spectral energy-distribution in illuminants and the visibility of radiation of various wave-lengths are necessary, therefore Table XXIII is presented. The relative energy-values at various wave-lengths are given for four illuminants which represent nearly the extremes commonly encountered from the viewpoint of color. In the last column are presented the visibility data[4] standardized in the 1918 report of the Nomenclature and Standards Committee of the Illuminating Engineering Society. There is no exact agreement as yet among investigators regarding the visibility of radiation of different wave-lengths, however, the data are sufficiently well established for the present purpose. On multiplying each ordinate of a spectral energy distribution curve of an illuminant, pigment, dye, etc., by the corresponding value of visibility, the resultant data yield the spectral luminosity-distribution of the illuminant, pigment, dye, etc. Thus, from the spectral energy and visibility data the relative spectral luminosity-values can be determined. On integrating the areas of the spectral luminosity curves, the relative total luminosity-values of colored media and of illuminants can be obtained and by dividing the area of one of the former by the area of one of the latter, the reflection-factor of the particular colored medium is obtained for the particular illuminant. Thus by computation, the reflection-factors of colored media can be obtained without any of the difficulties and

TABLE XXIII

Spectral Energy-Distribution in Common Illuminants and the Visibility of Radiation

Wave-length	Blue sky	Noon sun	Tungsten (vacuum) Incandescent Lamp 7.9 lumens/watt	Tungsten (gas-filled) Incandescent Lamp 22 lumens/watt	Visibility of radiation* Relative to that at 556$\mu\mu$	Visibility of radiation* Absolute (Lumens per watt)
0.40μ	170	67	9	15	0.0004	0.0000006
.41	177	72	9.5	16.5	.0012	.0000018
.42	181	75	10.5	19	.0040	.0000060
.43	185	79	12	23	.0116	.000017
.44	186	83	15	26.5	.023	.000034
.45	187	84.3	16.7	30	0.038	0.000057
.46	185	88	20	33.7	.060	.000090
.47	180	91	23.5	38	.091	.000136
.48	173	92	27	42.6	.139	.000208
.49	162	92.5	32.7	47	.208	.000312
.50	157	95	37.5	52	0.323	0.00048
.51	146	96	42.6	56.5	.484	.00073
.52	140	97	49	62	.670	.00100
.53	132	98	54.9	67	.836	.00125
.54	127	99	62.1	72.5	.942	.00142
.55	120	99	68.6	78	0.993	0.00149
.56	115	100	76	83	.996	.00149
.57	108	100	83.4	88	.952	.00143
.58	104	101	91	94	.870	.00130
.59	100	100	100	100	.757	.00114
.60	97	100	108	105	0.631	0.00095
.61	93	100	117	111	.503	.00075
.62	90	99	126	116	.380	.00057
.63	87	98.5	136	121.5	.262	.00039
.64	85	98	146	126	.170	.00025
.65	82	97.1	157	131	0.103	0.000154
.66	80	96	167	135	.059	.000089
.67	77	95.5	179	140	.030	.000045
.68	76	94	189	143	.016	.000024
.69	72.5	93.5	202	147.5	.0081	.0000122
.70	71	91.7	212	151	0.0041	0.0000061
.71	69.6	90	223	153.5	.0021	.0000031
.72	68	88	235	156	.0010	.0000015

* Standardized in 1918 Report of Committee on Nomenclature and Standards of I.E.S.

uncertainties of color-photometry, for these have been involved in the determination of the visibility data. Such computations are found to yield results quite in

agreement with those obtained by direct measurement of reflection- (or transmission-) factor. In fact, this method appeals very strongly to the author, especially because the spectral analyses should be available for many other reasons so that reflection- and transmission-factors would be by-products.

The spectral luminosity-distributions of the visible radiation reflected from pigments whose spectral re-

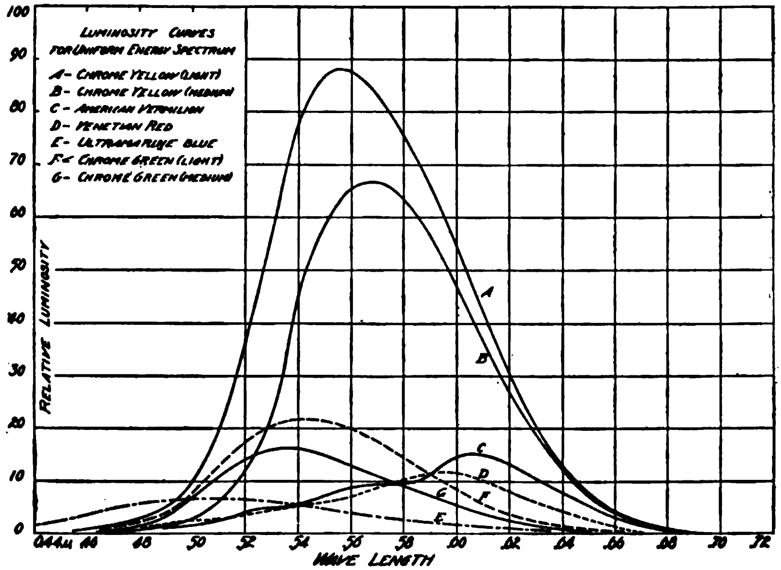

Fig. 133. — Pigments.

flection-factor distributions are shown in Figs. 131 and 132 and in Table XXII are presented in Figs. 133 and 134. These may also be considered as the spectral reflected-energy distributions for an imaginary illuminant of uniform spectral energy-distribution. Incidentally, the light from the noonday sun approaches this ideal fairly closely as seen by Table XXIII for in this table the energy-values of this ideal illuminant would be 100 for all wave-lengths in order to be directly comparable with the other illuminants.

93. *Reflection-factor of Pigments.* — In order to cover the general case more accurately much of the foregoing discussion will be expressed mathematically but, for the sake of clearness, reference will be made to these various curves in Fig. 135 for a specific case.

I = Spectral energy-distribution of an illuminant (tungsten filament at 7.9 lumens per watt).

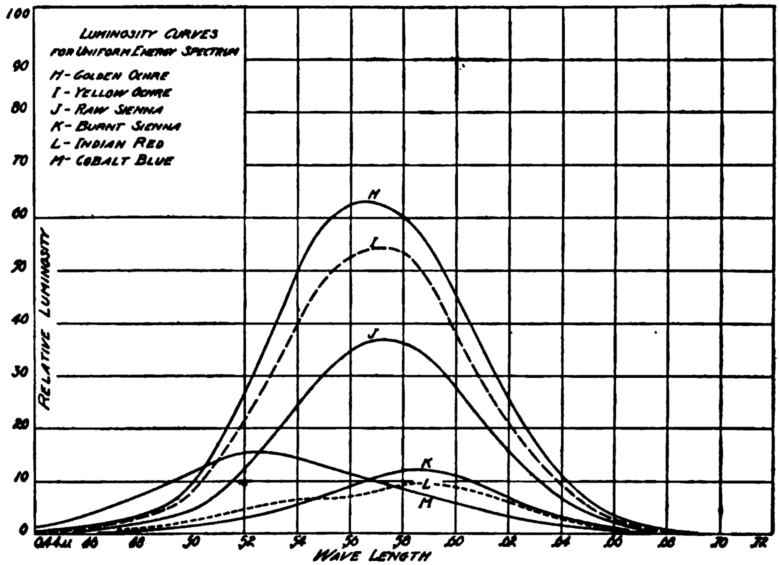

Fig. 134. — Pigments.

J_λ = Energy-value of the illuminant at any wave-length, λ.

V = Visibility curve.

K_λ = Visibility-value for energy of wave-length, λ.

L_I = Spectral luminosity-distribution of illuminant I.

P = Spectral reflection-factor distribution of a pigment (light chrome yellow).

R_λ = Reflection-factor of the pigment for energy of wave-length, λ.

L_P = Spectral luminosity-distribution of radiant energy reflected by the pigment.

For $\lambda = 0.52\mu$, $ad = J_\lambda$, $af = K_\lambda$, $ae = R_\lambda$, $ac = K_\lambda J_\lambda$, and $ab = R_\lambda K_\lambda J_\lambda$.

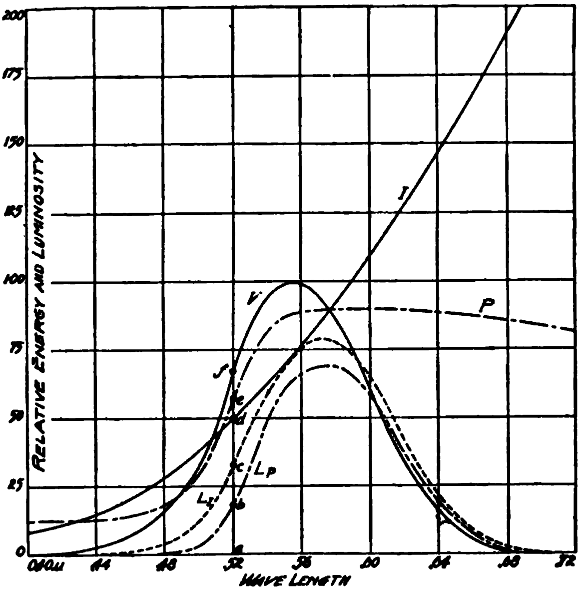

Fig. 135.—Analysis of a pigment.

$\int_{\lambda_1}^{\lambda_2} K_\lambda J_\lambda d\lambda$ = Area enclosed by L_I, which is proportional to the total luminous flux E, received by the surface between limits λ_1 and λ_2, hence is equal to CE where C is a constant of proportionality. If the total is desired, the limits, λ_1 and λ_2, are respectively the limits of the visible spectrum which for most practical cases may be taken as 0.4μ and 0.7μ.

$\int_{\lambda_1}^{\lambda_2} R_\lambda K_\lambda J_\lambda d\lambda$ = Area enclosed by L_P, which is proportional to the total luminous flux, E', reflected by the surface (pigment P) and is equal to CE'.

If energy is of interest instead of luminosity, K_λ is eliminated and the limiting wave-lengths λ_1 and λ_2 are given the desired values.

$$\frac{\int_{\lambda_1}^{\lambda_2} R_\lambda K_\lambda J_\lambda d\lambda}{\int_{\lambda_1}^{\lambda_2} K_\lambda J_\lambda d\lambda} = \frac{E'}{E} = R =$$

the reflection-factor of the pigment P for the illuminant I, and λ_1 and λ_2 are respectively the wave-lengths at the limits of the visible spectrum. These limits could be expressed as 0 and ∞ without changing the result because beyond the visible spectrum K_λ is zero.

Many useful data can be obtained by such computations when the spectral energy-distributions of pigments and of illuminants are available. These computations can be made for a sufficient number of wave-lengths throughout the spectrum and the relative values of the integrals can be obtained by means of a planimeter from the plotted curves or more readily by summating the computed values.

Similar computations have been made for the group of pigments already introduced for four illuminants including the ideal having a uniform spectral energy-distribution. These values are presented in Table XXIV and Fig. 136. The values are given to the third decimal place not with the belief that the absolute values are determined with such accuracy but to show the differences as accurately as possible obtained by this method of computation. The relative values are perhaps accurate to the third place. It is seen that the reflection-factor for a given pigment is not constant (see # 42) but varies with the illuminant. This is a point not generally appreciated and inasmuch as this difference exists the suggestion is made that, for general purposes, reflection-factors be given for an illuminant of uni-

TABLE XXIV

Absolute and Relative Total Reflection-factors of Thick Layers of Powdered Pigments for Various Illuminants

	Absolute				Relative			
	Uniform energy-spectrum	Noon sun	Blue sky	Tungsten filament 7.9 lumens per watt	Uniform energy-spectrum	Noon sun	Blue sky	Tungsten filament 7.9 lumens per watt
American vermilion......	0.137	0.137	0.117	0.117	1.00	0.99	0.86	1.29
Venetian red...........	.106	.106	.095	.131	1.00	1.00	.90	1.23
Tuscan red.............	.107	.107	.101	.12	1.00	1.00	.95	1.12
Indian red.............	.099	.099	.092	.112	1.00	1.00	.93	1.13
Burnt sienna...........	.105	.106	.093	.127	1.00	1.01	.89	1.19
Raw sienna.............	.324	.326	.303	.366	1.00	1.01	.94	1.13
Golden ochre...........	.578	.581	.548	.634	1.00	1.01	.96	1.10
Chrome yellow ochre....	.328	.33	.289	.404	1.00	1.00	.91	1.24
Yellow ochre...........	.488	.488	.46	.534	1.00	1.01	.95	1.11
Chrome yellow (med.)...	.542	.545	.496	.63	1.00	1.01	.92	1.16
Chrome yellow (light)....	.76	.765	.70	.82	1.00	1.01	.92	1.08
Chrome green (light)....	.19	.194	.19	.175	1.00	1.00	1.03	.93
Chrome green (med.)....	.136	.136	.142	.12	1.00	1.00	1.05	.88
Cobalt blue.............	.166	.162	.183	.13	1.00	.98	1.10	.79
Ultramarine blue........	.08	.074	.095	.057	1.00	.93	1.19	.71

TABLE XXV

Spectral Transmission-factors of Certain Solutions of Red Dyes

	0.44μ	0.46μ	0.48μ	0.50μ	0.52μ	0.54μ	0.56μ	0.58μ	0.60μ	0.62μ	0.64μ	0.66μ	0.68μ	0.70μ
Carmen ruby opt.	....	....	....	....	....	....	....	....	....	.04	.18	.37	.49	.60
Amido naphthol red	....	....	....	....	....	....	....	....	.04	.38	.75	.92	.96	.96
Coccinine	....	....	....	....	....	....	....	.04	.56	.96	.98	.98	.98	.98
Erythrosine	.06	....	....	....	....	....	.01	.53	.90	.95	.96	.96	.96	.96
Hematoxyline	.01	.03	.07	.13	.14	.12	.13	.25	.44	.54	.63	.73	.78	.82
Hematoxyline	....	....	....	....	....	....	....	.01	.02	.04	.09	.15	.21	.25
Alizarine red	.01	.01	.02	.03	.04	.06	.11	.22	.39	.54	.65	.72	.77	.79
Acid rosolic (pure)	.04	.03	.01	....	....	....	.02	.38	.78	.88	.90	.91	.92	.92
Rapid filter red	....	....	....	....	....	.01	.10	.47	.86	.95	.96	.96	.96	.96
Aniline red Fast extra A	....	....	....	....	....	.02	.12	.34	.55	.72	.84	.88	.90	.92
Pinatype red F	....	....	....	....	....	....	....	....	.11	.35	.55	.65	.68	.69
Eosine (yellowish)	....	....	....	....	....	....	....	....	.06	.40	.63	.74	.82	.85
Eosine	....	....	....	....	....	....	.01	.54	.87	.93	.92	.92	.92	.92
Naphthalinrot in abs. alcohol	....	....	....	....	....	....	....	....	.06	.28	.43	.50	.57	.61
Rose bengal	.80	.70	.34	.06	.01	....	.14	.82	.96	.97	.98	.98	.98	.98
Rose bengal	.01	....	....	....	....	....	....	.09	.57	.83	.89	.92	.94	.96
Cobalt ammon sulphate	.60	.56	.48	.37	.38	.53	.70	.82	.86	.90	.90	.90	.90	.89
Cobalt nitrate	.69	.51	.40	.31	.32	.48	.67	.82	.87	.90	.90	.90	.90	.90

TABLE XXVI

Spectral Transmission-factors of Certain Solutions of Yellow Dyes

	0.44μ	0.46μ	0.48μ	0.50μ	0.52μ	0.54μ	0.56μ	0.58μ	0.60μ	0.62μ	0.64μ	0.66μ	0.68μ	0.70μ
Tartrazine	....	....	....	....	.07	.52	.75	.86	.91	.95	.96	.97	.98	.98
Chrysoidin	....	....	....	....	....	....	....	....	.02	.23	.50	.71	.79	.79
Aurantia	....	....	....	....	....	.03	.23	.53	.82	.92	.96	.96	.96	.96
Aniline yellow phosphine	....	....	....	....	.02	.20	.43	.60	.67	.75	.81	.85	.86	.87
Fluorescein	.15	.01	....	....	.48	.91	.97	.98	.98	.98	.98	.98	.98	.98
Aniline yellow Fast S.	....	....	.01	.07	.43	.84	.96	.96	.96	.96	.96	.96	.96	.96
Methyl orange indicator	....	....	....	....	....	....	.01	.31	.70	.79	.80	.81	.81	.81
Auramin	....	....	.01	.39	.77	.83	.84	.86	.87	.88	.90	.92	.93	.93
Uranine	.15	.01	....	.01	.58	.96	.97	.97	.97	.97	.97	.97	.97	.97
Uranine naphthaline	....	....	....	.04	.53	.77	.82	.83	.84	.85	.86	.86	.87	.87
Orange B naphtol	....	....	....	....	....	.01	.43	.88	.95	.96	.97	.97	.97	.97
Safranine	....	....	....	....	....	....	....	....	.03	.27	.64	.85	.93	.93
Martius gelb	....	....	....	.01	.43	.84	.91	.94	.95	.95	.95	.95	.95	.95
Naphtol yellow	....	....	.01	.18	.74	.91	.96	.97	.98	.98	.98	.98	.98	.98
Potassium bichromate (sat.)	....	....	....	....	....	.10	.60	.84	.88	.89	.89	.89	.89	.88
Cobalt chromate	.17	.36	.62	.82	.88	.90	.92	.93	.95	.96	.96	.96	.96	.95

TABLE XXVII

Spectral Transmission-factors of Certain Solutions of Green Dyes

	0.44μ	0.46μ	0.48μ	0.50μ	0.52μ	0.54μ	0.56μ	0.58μ	0.60μ	0.62μ	0.64μ	0.66μ	0.68μ	0.70μ
Naphtol green........	.02	.04	.07	.21	.30	.36	.29	.16	.07	.02	.01	....	....	....
Brilliant green.......	.04	.39	.69	.52	.23	.04	....	....	....	....	....	.02	.23	.64
Filter blue-green.....	.35	.49	.64	.70	.60	.37	.13	.02	....	....	....	....	....	....
Filter blue-green.....	.06	.14	.23	.40	.26	.08	.01	....	....	....	....	....	....	....
Malachite green......	....	.12	.20	.08	.01	....	....	....	....	....	....	....	.12	.50
Malachite green......	....	.01	.04	.01	....	....	....	....	....	....	....	....	.02	.23
Malachite green......	....	....	.01	....	....	....	....	....	....	....	....	....	....	.10
Saurgrün............	.03	.29	.57	.57	.39	.19	.04	.01	....	....	....	....	.04	.30
Methylengrün........	.28	.31	.32	.26	.17	.07	.02	.01	....	....	....	....	.03	.28
Methylengrün........	.14	.16	.17	.13	.06	.01	....	....	....	....	....	....	.02	.14
Aniline green Naphtol B	.02	.06	.14	.24	.34	.40	.32	.14	.04	.01	....	....	....	....
Aniline green Naphtol B	....	....	.02	.06	.10	.15	.09	.02	....	....	....	....	....	....
Neptune green.......	....	.40	.63	.41	.13	.01	....	....	....	....	....	....	....	.05
Neptune green.......	....	.19	.36	.18	.02	....	....	....	....	....	....	....	...	.02
Cupric chloride.......	.77	.84	.89	.92	.92	.89	.80	.67	.52	.36	.19	.06	.02	....

form spectral energy-distribution. In cases of direct measurement of these factors the clear noon-day sun sufficiently approaches the ideal as will be shown shortly. In cases where other illuminants are used these should be specified.

The measurement of reflection-factor directly is by no means standardized and in the case of colored pig-

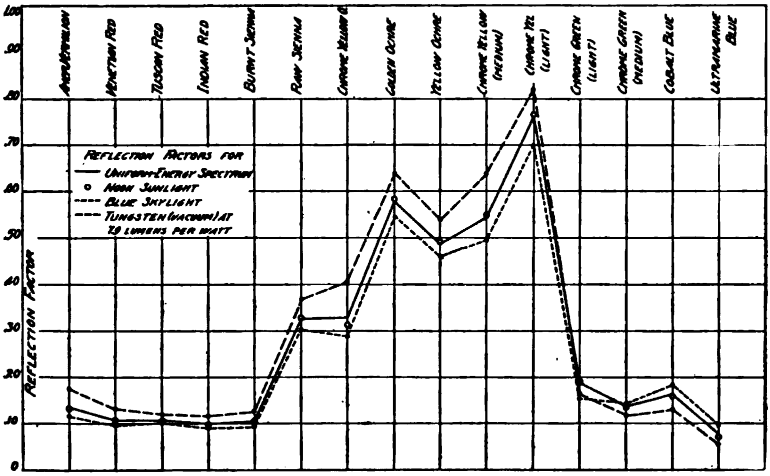

Fig. 136. — Pigments.

ments this measurement is attended with many difficulties such as the distribution of luminous flux upon the surface, its angular position with respect to the photometer, color-photometry, etc. A discussion of this has been presented elsewhere.[5]

In Table XXIV the relative reflection-factors of each pigment by itself for the four illuminants are presented, that for the uniform energy-spectrum being taken as unity. This gives a better idea of the magnitude of the variation of the reflection-factor with the spectral character of the illuminant. These values are plotted in Fig. 137 and as would be expected, the red and yellow

pigments show relatively greater reflection-factors for tungsten light than for blue sky-light with the values for sunlight (circles) lying between. It is interesting to note the proximity of the circles to unity which represents the relative value of reflection-factor in each case for the ideal illuminant having an uniform spectral energy-distribution.

The effect of the illuminant upon the appearance of

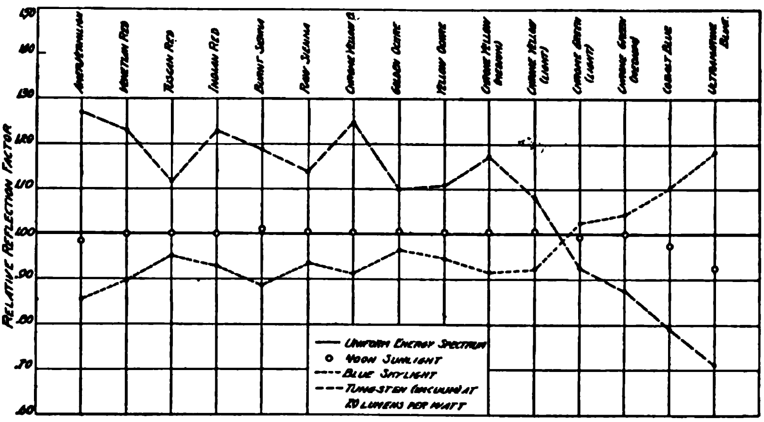

Fig. 137. — Pigments.

the color is shown in Fig. 138 using, for example, ultramarine blue whose spectral energy-distribution is shown. The spectral luminosity-distributions of this pigment for the different illuminants have been computed for equal total amount of reflected light (enclosed areas equal). Thus an idea of the appearances of the color can be formed or conversely the reason for these different appearances under the three illuminants is manifest. Incidentally, it is seen that the pigment is of a purer color under blue skylight than under either of the other illuminants. The wave-length of maximum luminosity is 0.495μ and 0.54μ respectively for the skylight and tungsten light. This wave-length of maximum lumi-

nosity is not necessarily the dominant hue of the color as analyzed by the eye or by the monochromatic colorimeter although these are often nearly coincident.

94. *Spectral Analyses of Dye-solutions.* — The mixture of dyes is governed by the same subtractive principles of color-mixture as the mixture of pigments although the greater number of dyes and the more

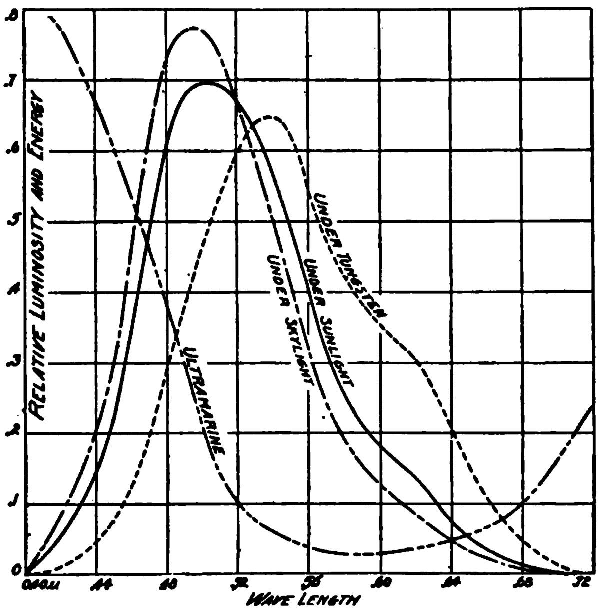

Fig. 138. — Ultramarine.

exacting or delicate applications of dyes in industries, in the making of accurate filters, etc., make their spectral analyses of perhaps more importance than in the case of pigments. Certainly, a knowledge of the spectral characteristics of dyes, as in the case of pigments, makes for an ease and certainty in making and in visualizing mixtures which cannot be enjoyed without such data. It is beyond the scope of this section to present a complete discussion of the usefulness of spectral analyses

of dyes or to present the spectral analyses of all the dyes available; however, a few representative analyses of dyes most common and perhaps most reproducible should be of value. These are presented in the following tables roughly classified as to color. The highest accuracy is not claimed for these data because it does not appear worth the effort necessary because there is no indication that these dyes are in general constant in spectral characteristics as obtained from time to time in the market. For the same reason it has not been considered necessary to give values of concentration. From the data presented in the tables it is possible to obtain an idea of the spectral characteristic of a given dye-solution for any depth of the particular concentration employed and also for any relative value of concentration. In other words, from the data in the tables and the discussion which follows it is possible to be guided in the selection of dyes for many purposes. For the study of a dye-solution throughout an entire range of depth and concentration by the method described later, the spectral analysis should be obtained as accurately as possible. In all cases where not indicated otherwise, the solvent was distilled water. The dyes were obtained from various well-known commercial sources. Among the solutions will be found a few solutions of metallic salts which are incorporated for their usefulness as filters. All data have been corrected for surface reflections and for the absorption of the glass cell by the method of substitution.

In Table XXV are presented the spectral analyses of a number of dye-solutions commonly classed as red although many are purple. The sharpness of the absorption- or transmission-bands is readily visualized from the data although it is of advantage to plot the data in many cases. There are some excellently sharp bands

shown, for example, that of eosine of moderate concentration. In some cases spectral analyses for two concentrations have been presented.

In Table XXVI spectral analyses of a number of yellows are presented. It is noteworthy that there is no known dye which transmits only a narrow region near spectral yellow. The value of sharp absorption-bands is seen when a fairly monochromatic filter is desired. For instance a yellowish green dye with a sharp cut-off on the long-wave side combined with a greenish yellow dye with a sharp cut-off on the short-wave side will yield a fairly monochromatic green filter. Some of the dyes fluoresce which from the point of view of color alone is of considerable interest. Fluorescein and uranine are among the many which fluoresce strikingly. It is interesting to study these by projecting a spectrum upon their upper liquid surface and by viewing the result both from above and from the side. The spectral analyses of potassium bichromate and cobalt chromate are included.

Among the greens in Table XXVII are a number of dichroics. In fact, a very common characteristic of green dyes is the exhibition of dichromatism. This can readily be ascertained by noting the energy-spectrum or spectral transmission characteristic of one of these dyes. If the transmission-factor for red, say 0.7μ, is in any one case greater than that for any wave-length in the other regions of the spectrum (in the green for so-called green dyes) the solution at great depths or concentrations will appear red and therefore will be dichroic. Naphthol green is an excellent yellowish green dye. Among the greens presented, malachite, saurgrün, methylengrün, and neptune green exhibit dichromatism.

One of the most annoying features of dyes is the extreme rarity of pure blue dyes. Nearly all blue dyes,

Table XXVIII, transmit the extreme red rays quite freely and the scarcity of blue-green dyes which are not dichroic makes it difficult often to find a combination which transmits only the violet rays. In extremely high concentrations or great depths some blue dyes effectually absorb most of the extreme red rays.

In Table XXIX are presented a number of spectral analyses grouped under the common name of purple for the purpose of classification. An interesting case is that of ethyl violet in gelatine both wet and dry. After the dyed gelatine, which was flowed on clear glass, had set, and while still wet the spectral analysis was made. The sample was then allowed to dry and another spectral analysis was made. On plotting these data a decided difference in the spectral transmission curves is seen as indicated by the numerical data. The wet specimen is decidedly more reddish than when dry and an actual shift in the absorption-band takes place on drying. Although not definitely established this may be explained as due to a difference in the refractive-index of the solvent in the two cases. The data are corrected for reflections from the gelatine and glass surfaces.

In Table XXX are presented spectral analyses of dyed gelatine filters before and after fading by exposure to solar radiation. Such data are of special interest in many cases and it appears of interest to make a thorough study of the fading of dyes with the aid of spectral analyses. Certainly no great amount of information is available regarding the relation of the spectral character of radiation to the spectral deterioration of dyes or the relation of either of these to the chemical composition. Incidentally, the testing of dyes under illuminants containing ultra-violet rays of extremely short wave-lengths which are practically absent in solar radiation at the earth's surface or in artificial illuminants as com-

TABLE XXVIII

Spectral Transmission-factors of Certain Solutions of Blue Dyes

	0.44μ	0.46μ	0.48μ	0.50μ	0.52μ	0.54μ	0.56μ	0.58μ	0.60μ	0.62μ	0.64μ	0.66μ	0.68μ	0.70μ
Turnbull's blue.......	.58	.60	.56	.51	.38	.28	.18	.09	.05	.03	.01	....	....	....
Victoria blau.........	.52	.23	.09	.01	....	....	....	....	....	.01	.04	.21	.49	.73
Prussian blue (soluble)	.66	.71	.76	.69	.60	.46	.32	.20	.12	.07	.05	.03	.03	....
Prussian blue (soluble)	.06	.09	.09	.05	.02	.01	....	....	....	....	....	....	....	....
Wässer blau.........	.89	.75	.51	.26	.07	.01	....	....	.01	.02	.06	.18	.37	.60
Wässer blau.........	.85	.66	.42	.17	.03	.01	....	....	....	.01	.03	.10	.26	.48
Resorcine blue.......	.25	.18	.06	.02	.01	....	....	....	.01	.02	.14	.41	.64	.72
Toluidin blau........	.66	.31	.13	.03	.01	....	....	....	....	....	.01	.04	.16	.40
Patent blue..........	.83	.91	.84	.76	.65	.46	.24	.08	.02	....	....	.06	.42	.78
Patent blue..........	.15	.25	.17	.05	....	....	....	....	....	....	....	....	....	.12
Dianil blue..........	.77	.69	.59	.48	.35	.24	.15	.09	.05	.05	.07	.14	.29	.53
Dianil blue..........	.38	.30	.18	.10	.04	.01	....	....	....	....	....	....	.02	.12
Filter blue...........	.84	.79	.66	.44	.27	.17	.14	.19	.36	.56	.74	.81	.88	.92
Filter blue...........	.35	.29	.18	.05	....	....	....	....	.02	.08	.23	.44	.62	.71
Aniline blue, methyl..	.92	.88	.78	.52	.27	.09	.03	.02	.02	.04	.08	.16	.25	.45
Aniline blue, methyl..	.44	.31	.13	....	....	....	....	....	....	....	....	....	....	....

TABLE XXIX

Spectral Transmission-factors of Certain Solutions of Purple Dyes

	0.44μ	0.46μ	0.48μ	0.50μ	0.52μ	0.54μ	0.56μ	0.58μ	0.60μ	0.62μ	0.64μ	0.66μ	0.68μ	0.70μ
Ethyl violet in gelatine (dry)	.97	.87	.67	.28	.04	....	....	....	....	.05	.33	.73	.88	.91
Ethyl violet in gelatine (wet)	.83	.79	.45	.07	.01	....	.01	.03	.05	.15	.42	.76	.91	.93
Magenta	.21	.06	.02	.01	....	....	.01	.22	.73	.93	.97	.97	.97	.97
Magenta	....	....	....	....	....	....	....	....	.07	.48	.81	.92	.95	.95
Gentiana violet	.89	.83	.64	.44	.26	.19	.15	.10	.13	.42	.75	.92	.93	.94
Gentiana violet	.11	.01	....	....	....	....	....	....	....	....	.01	.15	.48	.66
Rosazeine	.50	.28	.02	....	....	....	....	.06	.55	.90	.98	.98	.98	.98
Rosazeine	....	....	....	....	....	....	....	....	....	.07	.54	.90	.95	.95
Iodine (dense)	....	....	....	....	....	....	....	....	....	....	.01	.03	.11	.23
Rhodamine B	.81	.71	.45	.13	.02	....	....	.23	.83	.96	.96	.96	.95	.94
Acid violet	.84	.76	.68	.50	.33	.26	.27	.34	.49	.70	.84	.96	.96	.96
Acid violet	.29	.08	.01	....	....	....	....	.01	.09	.32	.63	.84	.94	.94
Cyonine in alcohol	.07	.01	....	....	....	....	....	....	....	....	....	.01	.13	.23
Xylene red	.39	.23	.01	....	....	....	....	.01	.27	.79	.97	.97	.97	.96
Xylene red	....	....	....	....	....	....	....	....	.01	.31	.79	.96	.96	.95
Methyl violet B	.25	.04	....	....	....	....	....	....	....	....	.03	.26	.63	.89

TABLE XXX

Spectral Transmission-factors of Faded and Unfaded Gelatine Filters

	0.44μ	0.46μ	0.48μ	0.50μ	0.52μ	0.54μ	0.56μ	0.58μ	0.60μ	0.62μ	0.64μ	0.66μ	0.68μ	0.70μ
Erythrosine	.81	.52	.14	.02	....	.02	.16	.65	.95	.96	.96	.96	.96	.96
Erythrosine (faded)	.76	.58	.27	.10	.02	.07	.34	.78	.94	.95	.95	.95	.95	.95
Aniline yellow Fast S	.51	.57	.66	.82	.94	.97	.98	.98	.97	.97	.97	.95	.93	.91
Aniline yellow Fast S (faded)	.58	.62	.67	.81	.90	.95	.95	.95	.95	.95	.95	.95	.92	.90
Neptune green	.21	.41	.44	.40	.28	.15	.04	....	....	....	....	....	.06	.35
Neptune green (faded)	.10	.60	.75	.65	.43	.15	.02	....	....	....	....	....	....	.12
Green for screens	.15	.34	.72	.93	.93	.83	.69	.45	.25	.12	.04	.05	.26	.61
Green for screens (faded)	.15	.38	.70	.89	.86	.77	.67	.48	.32	.19	.09	.13	.42	.73
Ethyl violet	.74	.69	.33	.08	....	....	....	....	....	....	.06	.40	.72	.83
Ethyl violet (faded)	.67	.53	.34	.12	.02	....	....	....	....	.02	.21	.54	.77	.85
Methylenblau	.79	.75	.59	.43	.27	.11	.08	.01	....	....	....	.01	.13	.44
Methylenblau (faded)	.58	.49	.40	.29	.19	.15	.10	.09	.09	.11	.22	.35	.46	.57
Rosazeine	.97	.97	.96	.77	.54	.31	.17	.91	.95	.96	.98	.98	.95	.94
Rosazeine (faded)	.97	.97	.96	.89	.72	.73	.79	.92	.95	.95	.98	.98	.95	.94

monly encountered is open to criticism. Spectral analysis has not been sufficiently utilized in permanency tests to warrant all the conclusions which have been drawn in this matter although some excellent work has been done.[6] Mott has shown that the results with the 'snow-white' flame arc in dye-fading are practically the same as those obtained in daylight. He states that the white flame arc at 25 amperes affords light at a distance of two feet more intense than summer sunlight. By focussing the image of a quartz mercury arc by means of a quartz lens, an intense illumination rich in ultra-violet rays may be obtained. The large incandescent lamps may also be used with success.

95. *Applications of Spectral Analyses of Dyes.* — The uses for spectral analyses of dyes are manifold, as in the case of any class of colored media. In general, they provide a physical basis for systematic color-mixture besides providing the necessary information for choosing dyes for many purposes. In many aspects of color-technology only the integral or subjective color is finally of interest but the author cannot refrain from emphasizing that even in such cases an intimate knowledge of colored media and their mixture cannot be attained without spectral analyses and that the combination of dyes becomes systematic with such data available.

With spectrophotometric apparatus well maintained, a complete spectral analysis can be made in about an hour although there is much room for improvement in such apparatus which will result in the saving of time. However, this is not a serious matter because for a given coloring material only one anlaysis need be made, as will be shown later, to provide information for all degrees of concentration or depth of solution. The author has available hundreds of spectral analyses which, after once obtained, are a perpetual source of information.

96. *Laws Pertaining to Colored Solutions.* — In order to simplify the study of coloring media, especially dyes and colored glasses, several simplifications have been made. These are based on theory and have been confirmed by experiment on a few typical specimens. In order to develop this procedure it is necessary to revert to some of the established laws. Lambert first stated that all layers of equal thickness of a transparent medium absorb equal fractions of the radiant energy which enters them. This is true for homogeneous or monochromatic radiation, but cannot be applied to the total absorption of radiant energy of many wave-lengths or of extended spectral character.

It follows from Lambert's law that if the thickness of the absorbing medium increases in arithmetical progression the radiation transmitted should decrease in geometrical progression.

Let J be the intensity of radiation of a given wave-length entering a layer dl, then—

$$-\frac{dJ}{dl} = kJ$$

On integrating this we obtain,

$$J = J_0 e^{-kd}$$

where J_o is the original intensity, J the intensity after traversing a thickness d, and k is a constant depending upon the substance and upon the wave-length of the radiant energy. Various terms have been applied to this factor such as absorption-index. In logarithmic form this equation is expressed as,

$$\text{Log}\,\frac{J}{J_o} = \log T_\lambda = -k_\lambda d \log e = -\epsilon_\lambda d$$

where T_λ is the transmission-factor for energy of wave-length λ, and the subscripts, λ, indicate the factors which

vary with the wave-length. Beer deduced the law that the absorption is the same function of the concentration of a dispersing absorbing substance as of the thickness of a single substance which may be expressed thus:

$$J = J_o A_\lambda^{cd} \text{ or } T_\lambda = A_\lambda^{cd} \text{ or } \log T_\lambda = cd \log A_\lambda$$

where c is the concentration, A is the transmission-coefficient or transmissivity and the other symbols represent the same factors as in the foregoing equations. The validity of Beer's law has been questioned by some and it appears that there is some doubt as to its validity in such cases as colloidal solutions. This law appears to hold when the absorbing power of a molecule is uninfluenced by the proximity of other molecules. Obviously, if any change takes place in the condition of the dispersed substance on altering the concentration the law will not hold. Incidentally, there is work to be done on the validity of this law in the cases of 'colloidal' glasses. Lambert's law appears to be firmly established.

In so far as the foregoing laws are valid (and it appears that this is true for all practical purposes such as described in this chapter) for a given solution long T_λ is proportional to d, and for a given depth, or containing cell, log T_λ is proportional to c. By the use of coordinate paper having a logarithmic scale along one axis and a uniform scale along the other, a great deal of interesting data can be obtained from one spectral analysis.

By means of the foregoing mathematical relations the spectral analyses of colored solutions (and colored glasses) of any thickness and concentration can be obtained from two determinations of spectral character which may be reduced to a single determination. Such a method has been found exceedingly practicable in preliminary reconnoitering in search of combinations of dyes for filters, in the development of colored glasses,

and in the study of many problems arising in color-technology.

Some examples will suffice to illustrate the uses of this scheme in practice. Assume a solution of methylengrün of either known or unknown concentration. A cell of a known thickness is filled with the solution and a spectral analysis is made. For such a purpose a fairly low concentration or small depth is chosen so that radiations of all wave-lengths which are of interest are appreciably transmitted. On logarithmic paper as previously described, a plot is made as shown in Fig. 139, the transmission-factors from the spectral analysis being plotted on the logarithmic scale vertically above the arbitrarily selected point on the abscissa axis in this case taken as unity. The abscissae scale may represent either concentration or depth and may be either a relative or an absolute scale. Straight lines are drawn through the points to a common point on the ordinate axis representing complete transparency or unity on this logarithmic scale. This is the common point if corrections have been made for surface reflections in the cell or from the glass surfaces in the case of a colored glass. If these corrections have not been made, the common point usually will be near 0.92 on the 'transmission axis' if two surface reflections must be accounted for. Each straight line represents the relation of log T_λ and depth or concentration for a certain wave-length. By extending these lines the spectral characteristic of any depth or concentration may be read from the corresponding vertical line. If the original spectral analysis has been made with care such a simple plot yields a vast amount of data.

97. *Dichromatism.* — Methylengrün has been chosen in Fig. 139 because it also illustrates the interesting case of dichromatism so commonly exhibited by

dyes. It is seen that the slope of the line for 0.72μ is less than any of the others. This is proof that the dye is a dichroic. Some lines are very steep which indicates a large value of the extinction coefficient A for radiation of these wave-lengths. From the plot it is seen that this dye, in solutions of high concentration or of great depth, will not be green but will be red.

Another interesting plot, of a similar nature but in-

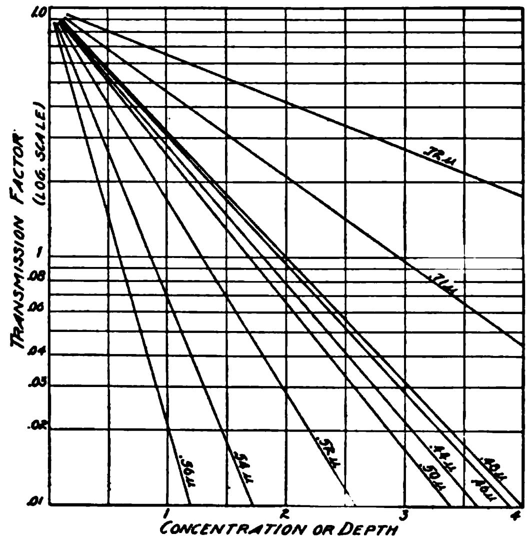

Fig. 139. — Methylengrün solution.

cluding relative luminosity-values instead of transmission-factors is shown in Fig. 140 for rosazeine. The spectral transmission-factors for the spectral analysis used were multiplied by the visibility of radiation in each case and plotted vertically above the point designated by unity on the concentration or depth scale. Instead of drawing straight lines representing various wave-lengths to a common point on the ordinate axis, each line is drawn to a point of this axis corresponding to the relative visibility of radiation of the particular

wave-length. The ordinate axis is now a logarithmic scale of relative luminosity. By extending these straight lines a graphical picture of spectral luminosity of the dye-solution is obtained for any concentration of depth. It is seen that this solution in great depth or high concentration becomes deep red because the slopes of the lines become less with increasing wave-length

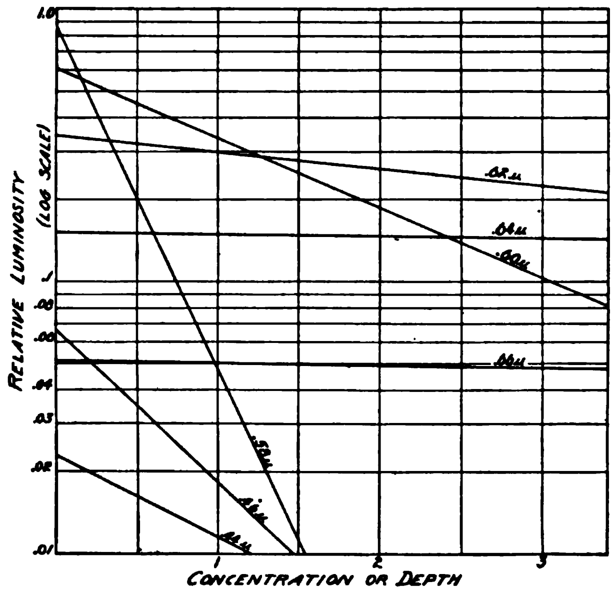

Fig. 140. — Rosazeine.

after the absorption-band of a weak solution or small depth is passed. Incidentally, it will be noted that the slope of line 0.44μ is less than that of 0.58μ which shows that in low concentrations or in relatively small depths of a higher concentration the solution is purple, that is, it has an absorption-band somewhere between 0.44μ and 0.60μ. Only a few wave-lengths have been used for the sake of clearness.

98. *Complete Representation of the Graphical Method.* — In reality the schemes illustrated in Figs. 139

and 140 are only completely illustrated by means of a solid of which, for example, Fig. 139 represents a projection upon the face of the solid bounded by the logarithmic 'transmission' scale and the concentration or depth scale. A model of this tri-dimensional diagram can be

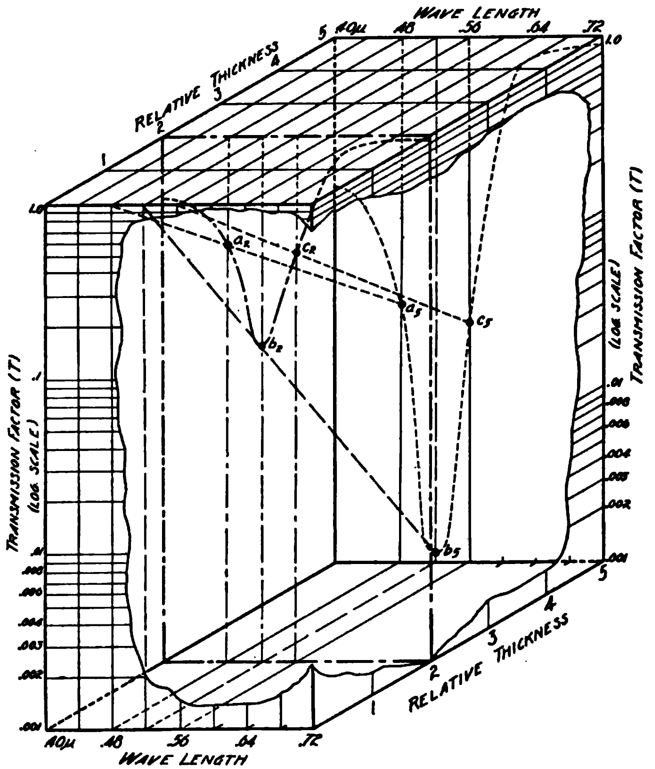

Fig. 141. — Graphical representation of laws of spectral transmission.

easily made and should be instructive. An attempt is made in Fig. 141 to illustrate the relations between transmission-factor, wave-length and concentration or thickness. For this purpose the spectral analysis of a thin piece of gold red glass was chosen. Many of the cross-section lines have been omitted for the sake of clearness. The scales are designated and the thickness

of the specimen of gold ruby glass is assumed to be 2 units on the relative thickness scale. In plane 2 represented by the dash-dot vertical rectangle, the spectral transmission is shown in the dash-dot curve $a_2b_2c_2$. For the limiting case of zero thickness, this curve becomes a straight line, $T = 1$, which is the top edge of the foremost rectangle, plane 0. Several points of the 'master' curve in plane 2, were taken for the purpose of illustrating the determination of the spectral characteristic of the glass at another thickness. In this example, thickness 5 units is taken and its spectral transmission is shown by the dotted curve in plane 5, the farthest vertical rectangle. This curve is obtained by drawing straight lines in the 'wave-length' planes from the wave-lengths on the upper front scale through the points on the 'master' curve in plane 2 of corresponding wave-lengths. Thus where a given straight line intersects the various thickness planes, the transmission-factors for that wave-length are found. For example, b_2 is a point on the 'master' curve in plane 2 and its value as read from the transmission-scale is the transmission-factor of this specimen of thickness, 2 units, for radiation of wave-length 0.52μ. A straight line drawn through this wave-length on $T = 1$ and through b_2 (always remaining in the particular wave-length plane) when prolonged intersects plane 5 at b_5 which is the transmission-factor for 0.52μ for a specimen of the same glass of 5 units thickness. Other points, a_5, c_5, etc., are found in the same manner.

These straight lines are the same as those shown in Fig. 148; in fact, Fig. 148 would be seen on viewing the solid, Fig. 141, from the righthand side. A model of this solid made of wires and painted to represent the spectral colors should be instructive.

In Fig. 140 luminosity-values were treated in a

manner similar to the transmission-values in Fig. 139. These also can be completely represented by a solid in a manner similar to that shown in Fig. 141 excepting that the vertical scale must represent logarithms of luminosity. In the limiting case of zero thickness the curve will not be the upper foremost horizontal line but will be the spectral luminosity-curve of radiation and will lie in the foremost vertical plane. On viewing such a solid in projection from the proper side, Fig. 149 will be seen if the same gold ruby specimen be taken as an example. It appears unnecessary to illustrate this possibility since the general procedure should be understood from the foregoing. In case the analysis is to be made for a particular illuminant the limiting curve in the foremost vertical plane will be the luminosity curve of the illuminant.

One of the points which is emphasized in dealing with colored media in the foregoing manner is that the spectral transmission- and reflection-factors are never zero but are merely relatively low for some wave-lengths as compared with others. This is often forgotten when spectral analyses are made with instruments because when the luminosity falls below the threshold the transmission-factor is considered to be zero; however, the threshold depends upon the intensity of illumination or upon the brightness of the light-source.

99. *Spectral Analyses of Glasses.* — In the development of colored glasses for the variety of practical applications, the spectral analyses are extremely valuable and often essential. By means of such data these coloring elements can be mixed computationally to obtain the desired spectral characteristic. From very meagre data on the chemical composition from one melt, fairly definite strides toward realization may be made in succeeding melts. Of course, there are chemical con-

siderations which sometimes alter the predictions based on computation; however, such a procedure forms a most definite working basis. In the combination of glasses for special filters, lighting effects, etc., the computational method often saves time and provides definite data. Sometimes only the subjective color is desired but even in these cases spectral analyses of elemental colorings provide the basis for manipulating the available vitrifiable colored media in a manner analogous to the combination of pigments.

In the manufacture of colored glass there is a limited number of coloring materials available and when the glass must be limited to one general composition, such as soda lime, for example, the colors which are possible of attainment are further limited. However, by combining various coloring materials, the variety of colored glasses can be enormously extended to meet the requirements of science and art.

In this chapter the spectral analyses of a few fundamental colored glasses will be presented and also the results of a few simple combinations. The record number of the specimen is placed before the symbol of the coloring metal such as 37 Se. If different relative thicknesses of the specimen are presented, a number is placed before the designation proper as 10(37 Se) indicates 10 units of thickness (or of concentration); CS indicates lime soda glass; PS, lead soda; BS, barium soda; P, lead, etc.

100. *Red.* — Selenium, copper, and gold are commonly used for producing red glasses. In Fig. 142 are shown the spectral analyses of a number of selenium glasses. It is seen that some of these are yellow in appearance, varying from this to a deep red. The composition of the mix is sometimes of considerable influence upon the final color. Specimen 14 Se shown in relative

thicknesses, 10, 20, and 34 was of unknown composition but the coloring element was selenium. This is a remarkable specimen. Cobalt blue glass (Fig. 146) transmits a deep red band, so a combination of dense cobalt blue and selenium glasses isolates a deep red band as seen in 6 Co + 14 Se, Fig. 142.

By computations similar to those presented in the

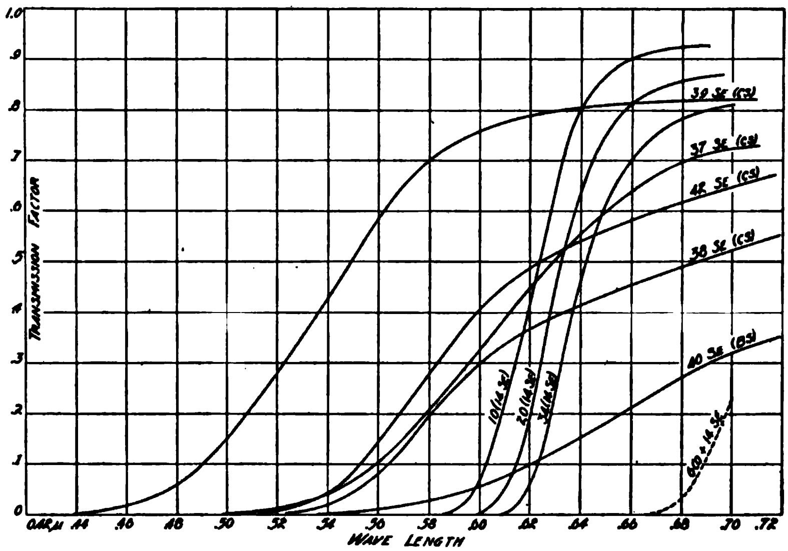

Fig. 142. — Red Glasses.

case of pigments (substituting transmission-factors, T_λ, for reflection-factors R_λ) the efficiency of such a combination in transmitting only a deep red band can be compared with that of a very dense selenium, gold, or copper glass. Unfortunately, at the ends of the visible spectrum the visibility data are least accurate; however, such relative comparisons by computation are dependable. Incidentally, Hyde, Cady, and Forsythe[7] have determined the visibility at the extreme red end of the visible spectrum with great care and Hartmann[8] at the blue end.

In Fig. 143 is shown the spectral characteristic of a copper red glass, 4 Cu, and in Fig. 144, the spectral analyses of gold glasses are presented. Gold produces a beautiful pink in low concentrations (or in thin layers) and deep red in the higher ones (or in thicker layers). The absorption-band is seen to be near 0.53μ for the more transparent glasses and it is interesting to note glass

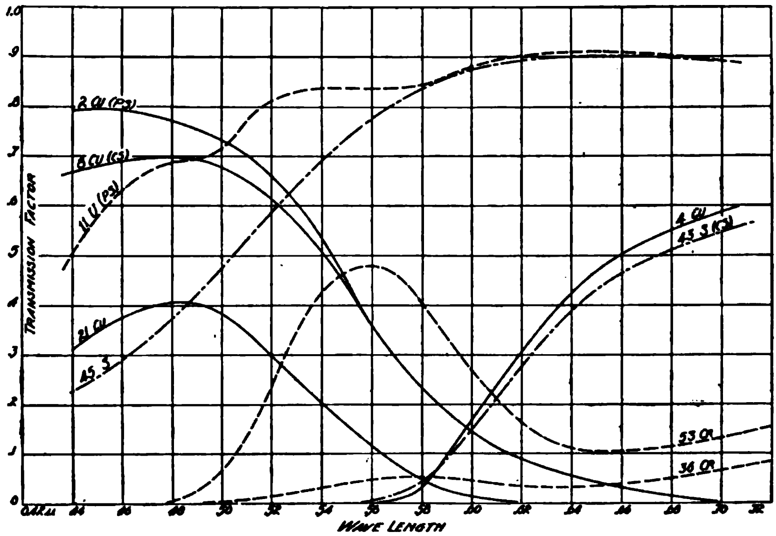

Fig. 143. — Copper, sulphur, uranium, and chromium glasses.

35 Au, a lead gold, which shows a shift in the absorption-band to 0.50μ. This glass was reheated several times in bringing out the color which is decidedly more ruddy and it appears that there is a different state of division of the metallic particles perhaps as to size. As the concentration or thickness increases (glass 5 Au, which is shown for three thicknesses) the blue band gradually disappears; however, the transmission does not closely approach monochromatism. In Fig. 144 are also shown the results of combining cobalt and gold glasses of different thicknesses (or concentrations), with the resulting transmission confined to the deep red region.

101. *Yellow.* — Carbon, sulphur, uranium, and silver are among those elements which, when introduced into glass under proper chemical conditions, produce yellow glasses of varying color. No single element isolates spectral yellow. In Fig. 145 are shown the spectral analyses of carbon yellow glasses, 15 C and 44 C, and of combinations of carbon yellow and light cobalt blue

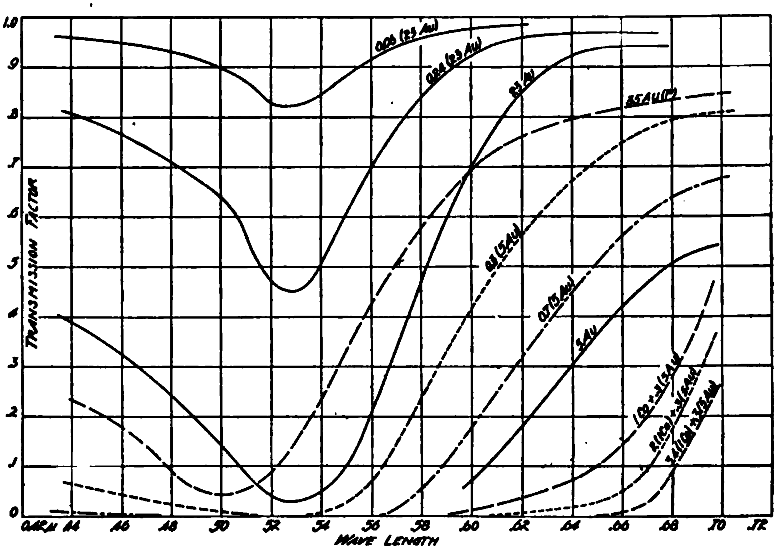

Fig. 144. — Gold and cobalt glasses.

glasses. It is known that X-rays, ultra-violet and visible rays will cause some clear glasses to become colored. In Fig. 145 is also shown the spectral characteristic of a glass X, which though originally clear was colored a muddy yellow throughout the mass by X-rays. It is interesting to observe the action of X-rays in discoloring glass, for it is easy at times to observe the progress of the coloring through the thickness of the glass. Patterns can be made by this process. In Fig. 143 are shown the spectral characteristics of uranium (11 U) and sulphur (43 S and 45 S) glasses. The spectral transmissions

of several uranium samples appear to be kinky in the blue-green region although the exact nature of the curves are not established.

102. *Green.*—Iron imparts a green color to glass varying from a bluish to a yellowish green, depending upon the ingredients of the glass. The importance of manganese in glass is as a decolorizing agent, its color

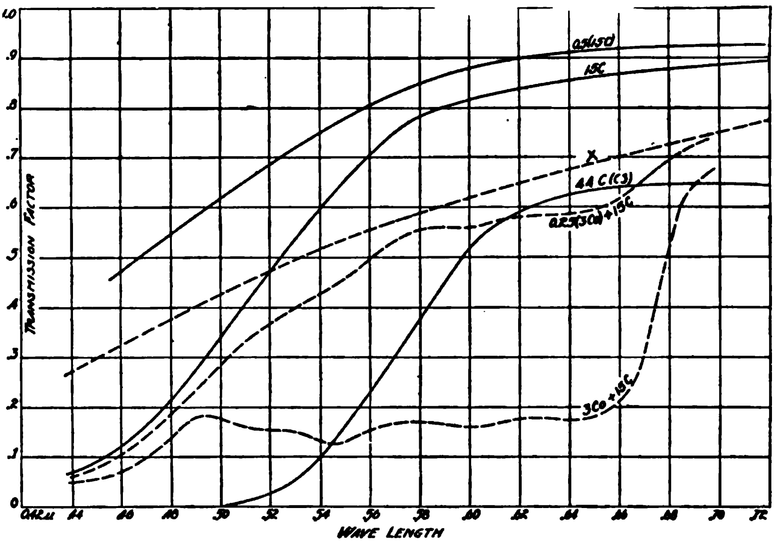

Fig. 145.—Yellow glasses and combinations with cobalt glass.

in proper concentrations being roughly complementary to that of iron commonly present in sand. Chromium imparts a yellowish green color to glass as seen in glass 53 Cr, Fig. 143. This glass has a maximum transmission at about 0.56μ and by the addition of copper blue-green (glasses 2 Cu and 8 Cu, Fig. 143) this maximum can be shifted toward the shorter wave-lengths depending upon the proportions of the coloring elements. Glass 21 Cu, called signal blue-green, is evidently a copper glass. Glass 36 Cr is a dense chromium green. In order to compare the actual colors under a given il-

luminant it is well to reduce these curves to luminosity values. If monochromatism is desired it is often advisable to combine two glasses which transmit a narrow region in common.

103. *Blue.*— Cobalt is the most common element used to impart a blue co or to glass. Its greatest disadvantage (although sometimes an advantage) is its

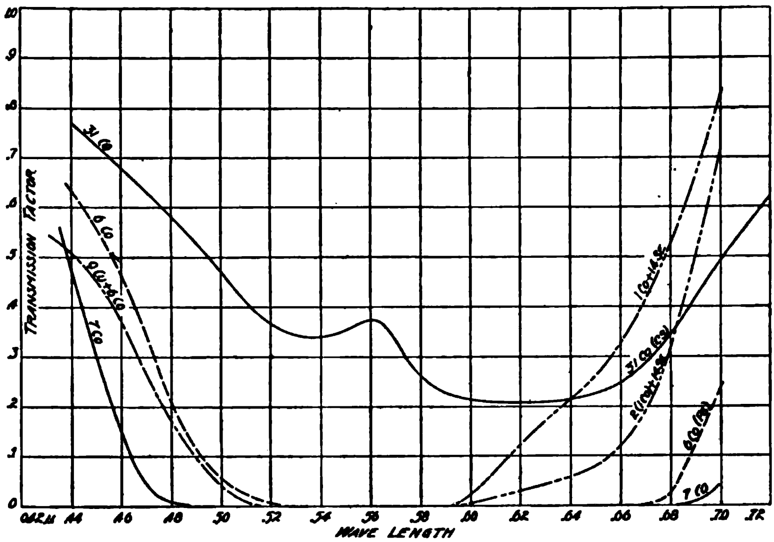

Fig. 146.— Cobalt glasses.

transmission of a deep red band as shown in 6 Co and 7 Co, Fig. 146. This red transmission can be utilized in isolating the deep red as shown by combining cobalt and selenium or other red glasses, for example, 1 Co + 14 Se. An excellent blue glass can be made by combining cobalt with copper blue-green, for the latter effectively absorbs the deep red. The spectral characteristic of such a combination is shown in 9 Cu + 6 Co, Fig. 146.

104. *Purple* — Nickel produces a purple color in glass and also manganese but the latter is not an efficient purple because its absorption-band is not sharp. Its

chief use is to neutralize the green tint due to the presence of iron in the ingredients of glass mixes. The spectral characteristic of a glass containing iron is shown in 41 Fe, Fig. 147. It is seen that a manganese glass of proper density is approximately complementary in color to the iron glass. Although the manganese neutralizes the iron in color, the transmission-factor of the resultant

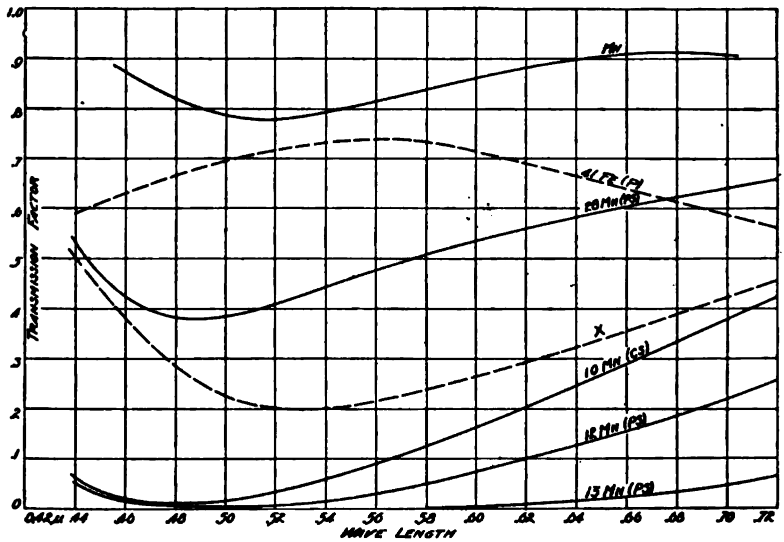

Fig. 147.—Manganese and iron glasses.

glass may be seriously reduced. Manganese, though a useful element in glass manufacture, cannot be considered important as a coloring element from the viewpoint of colored glasses in general. In X, Fig. 147, is shown the spectral characteristic of an originally clear glass which has been colored a deep purplish hue by exposure to X-rays. Undoubtedly this coloring is due to an effect upon the manganese present in the clear glass. This effect is commonly observed in lamp globes and window glass exposed to strong sunlight. In the former cases it is a very serious defect of glass manu-

facture because the author [13] has observed such globes whose transmission has been reduced as much as 50 per cent. after long exposure to intense solar radiation or to that emitted by an arc lamp. It would be far better in such cases as street-lighting glassware to eliminate the manganese and to endure the unneutralized greenish hue of the iron which is unavoidably present.

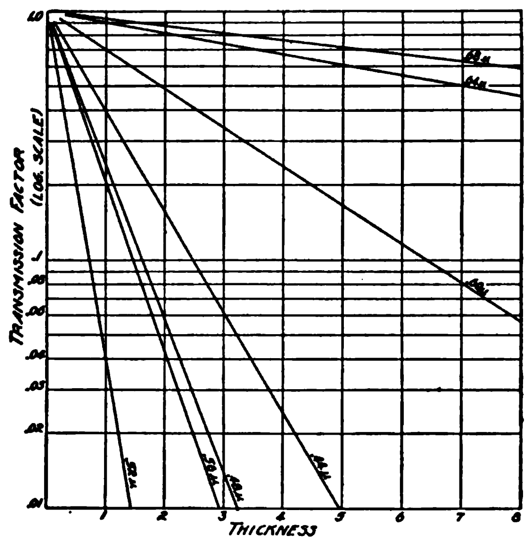

Fig. 148. — Gold ruby glass.

105. *Use of Spectral Analyses of Glasses.* — The applications for spectral analyses of colored glasses have been fairly well covered in the discussions of pigments and dyes, for the same general procedures can be applied to colored glasses. The concentration is not so definite as in the case of dyes because, owing to the high temperature at which glass melts and to chemical action, the concentration of coloring material in the final glass cannot always be predicted from the amount of coloring metal added to the mix. Some of the metals such as cobalt and copper, under standardized conditions of

melting, appear to produce concentrations of coloring material proportional to the amounts of the oxides added to the mix but in some cases there is doubt as to this proportionality. There is need for systematic study in

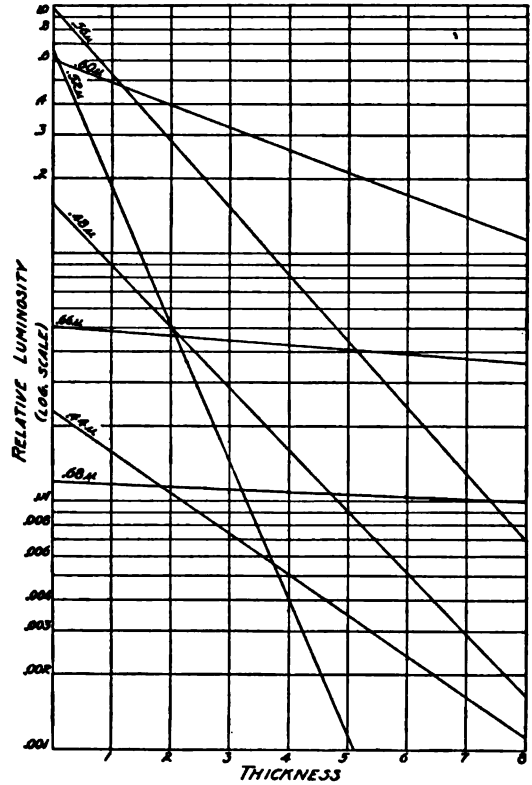

Fig. 149. — Gold ruby glass.

this direction. In the case of the red glasses, for example, gold ruby, which in ordinary manufacture assumes its red color on reheating, the manipulation has considerable effect upon the density of the color. After a colored glass has been obtained it is possible to procure from a single spectral analysis the integral transmission-factor for any illuminant, the spectral characteristics of other

thicknesses, and those of combinations of these thicknesses with other colored glasses as already outlined.

For the sake of further exemplification, in Fig. 148 are shown the straight-line relations between thickness and transmission-factor (for entering radiation) for several wave-lengths for various thicknesses of a gold ruby glass. The relations between luminosity and

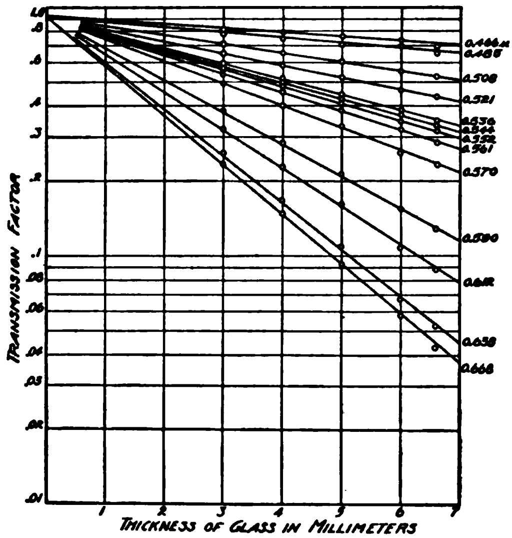

Fig. 150. — Test of 'straight-line' law.

thickness for this glass are shown in Fig. 149 for various wave-lengths. Fig. 148 is a diagram of what would be seen if the solid represented in Fig. 141 were viewed from the right-hand side.

At this point it is of interest to show the approximation of experimental results to the relations between spectral character and thickness as predicted by theory. This is shown in Fig. 150 for one of the glasses made during the development of an 'artificial-daylight' glass some years ago. The method of graphical analysis was tested because of the desire for a simple method and the speci-

men was ground and polished in five thicknesses. The circles show the verification of the theory. In this case correction had not been made for surface reflection so the straight lines must be drawn to a point near 0.92 on the transmission-axis. Incidentally, it is of interest to note that previous to the adoption of this method, samples of melts were ground in the form of thin wedges and spectral analyses were made at various thicknesses. It is seen that the graphical method enormously reduces the amount of work in order to obtain the data necessary for such studies.

In developing a colored glass for a specific purpose, various factors are considered such as the illuminant to be used and the result to be obtained. From these an ideal spectral transmission-curve is determined and by means of a few spectral analyses of different colored glasses, bearing in mind the chemical considerations if a mixture is finally necessary, various combinations can be made with the aid of the graphical method.

Often the ultra-violet and infra-red spectral transmissions are of interest and these are made in the manner already described. The data on a coloring element is not considered to be sufficiently complete for record if the ultra-violet transmission is not studied at least qualitatively and in some cases the infra-red transmission is investigated.

106. *Influence of Temperature on Transmission of Colored Glasses.* — Hyde, Cady, and Forsythe[9] in studying red pyrometer-glasses, noted the influence of temperature on the transmission characteristic of a red glass and investigated this influence for temperatures from 20° to 80° C. The transmission-factor of the red glass was found to be appreciably less for various wave-lengths at the higher temperatures than at the lower temperatures.

It appeared of interest to ascertain how generally the transmission-factors of colored glasses were affected by temperature.[10] In a preliminary study it did not appear worth while to investigate this question spectrophotometrically; therefore, only the transmission-factor for total visible radiation was considered. However, an idea of the change in spectral transmission is gained through the change in color of the specimen as its temperature is altered. It is hoped that at a later date a careful study of this phenomenon can be made spectrophotometrically and in parallel with chemical investigations.

In order to eliminate the annoyance of large color-differences in determining the transmission-factors at different temperatures, a given specimen was cut into two pieces and one was kept at a temperature of 30° C., while the temperature of the other was altered gradually from this temperature to 350° C. The transmission-factor of a colored glass, of course, varies with the illuminant so that such a value is indefinite unless the illuminant is specified. In this account it appears sufficient to state that the illuminants used were gas-filled Mazda lamps operating at normal voltage. A continuous check on the constancy of the light-sources and of the transmission-factors of the optical paths was made possible by removing the two colored glasses from the optical paths momentarily without altering the temperature conditions. The relative transmission-factors of the two pieces of the given specimen were measured throughout the range of temperature indicated and the results for ten commercial specimens are given in the diagram and in Table XXXI.

No color-difference was encountered during the measurements except that due to a change in the spectral transmission characteristic of the heated specimen. This color-difference became very marked for specimens

TABLE XXXI

Specimen	Principal coloring element	Color		Relative transmission-factors at various temperatures (centigrade)				
		Cold	Hot	30°	100°	200°	300°	350°
1	Copper	Medium red	....	100	97	92	87	84
2	Cobalt	Light blue	....	100	101	104	107	108
3	Cobalt	Deep violet	Deep blue		No appreciable change			
4	Gold	Pink	Violet	100	99	98	94	93
5	Copper	Blue-green	Yellow-green	100	98	94	87	82
6	Manganese	Purple	Blue-violet	100	97	94	91	90
7	....	Lemon-yellow	Orange	100	94	84	75	71
8	....	Dull yellow	....	100	98	94	91	90
9	Copper	Deep red	....	100	86	67	50	42
10	Chromium	Yellowish green	Yellow	100	95	84	72	67

5 and 10. The transmission-factor of the hotter piece is given in terms of that of the colder piece of the same specimen at the various temperatures — that is, the transmission-factors as given are relative values and not absolute. The color of a specimen at the highest temperature is given as compared with that of a piece of the same specimen at 30° C., the change being sufficient to be readily described in terms of our ordinary indefinite terminology. All the glasses excepting the two containing cobalt decreased in transmission-factor as the temperature increased, and in some cases this decrease in transmission-factor was very large. The curves obtained by plotting temperature and relative transmission-factor are, in general, approximately straight lines indicating that throughout this range of temperature the transmission-factor changes approximately proportionally with the temperature for the specimens used. Owing to the relatively slight change in hue in the red end of the spectrum, the red glasses 1 and 9 did not change appreciably in color when heated, notwithstanding large decreases in their transmission-factors.

This preliminary study indicates an interesting field for careful research which might throw more light upon the question, 'How are glasses colored?' It will be noted that the highest temperature studied is below that at which the glass becomes self-luminous or plastic. It will be of interest to carry this investigation close to the melting point. The results obtained are of interest both theoretically and practically.

107. *Ultra-violet Transmission.* — Another interesting fact reported by the author [11] is the increase in transmission of clear glass for certain ultra-violet rays by the addition of cobalt. In other words, the range of transmission extended further in the ultra-violet region in the case of the cobalt glass than in the case of the

clear glass, the slight amount of cobalt in the former being the only difference in the compositions of the two glasses.

Absolam [12] has presented the data in Table XXXII which indicate the wave-lengths where complete absorption commences; that is, in each case the wave-length indicating the longest one of the region of practically complete absorption. He used an arc between copper poles and a quartz spectrograph.

TABLE XXXII

Natural blue rock salt	Beyond 225$\mu\mu$
Natural rock salt colored by cathode rays	" 225
Natural rock salt colored blue by cathode rays	" 225
Sylvite white	" 225
Chile saltpetre, ordinary white variety	351
" " violet	325
Fluorspar, colored deep violet by cathode rays	Beyond 225
Diamond, yellow	320
Diamond, blue	315
Kunzite	305
Garnet	402
Zircon, (hyacinth) red-brown	262
Zircon, decolorized by heat	244
Zircon, green	402
Zircon, yellow	402
Topaz, pale yellow	262
Topaz, dark yellow	229
Topaz, pale pink-brown	262
Topaz, blue	296
Emerald	320
Ruby	300
Tourmaline, green	351
" green-yellow	300
" pink	306
Spinel, blue	402
" purple	325
" pink	300
Kyanite, blue	320
Beryle, blue	327
Cordierite, blue-purple	325
Cairngorm	325

Ordinary clear glass is practically opaque beyond 300$\mu\mu$ although clear glasses vary considerably in trans-

parency to ultra-violet depending upon the content of silica and other ingredients. In general, the color of a substance is no indication of its transparency to invisible radiation.

108. *Compounds Sensitive to Temperature.*—Experience with the effect of temperature on colored glasses leads to the belief that the same effect would be found with pigments and solutions. In fact, some of these effects have been noticed and it would be of interest to investigate this point systematically. Certain compounds change color with change in temperature and they are of practical as well as of scientific interest.

The double iodide of mercury and silver is normally a light yellow but its color changes to a deep orange or red at about 50° C. Its color will return to normal on cooling unless it has been overheated. It is prepared from separate aqueous solutions of silver nitrate and potassium iodide. The latter is added to the former until the original precipitate is dissolved. At this point a strong solution of mercuric chloride is added and the precipitate formed is the bright yellow double iodide of mercury and silver. This is filtered, washed, and dried. It may be used as a paint by mixing into a solution of gum arabic.

The double iodide of mercury and copper is normally red but changes to black at about 85° C. returning in color to red as it cools. This is prepared in a manner similar to the compound in the preceding paragraph excepting that copper sulphate is substituted for silver nitrate.

109. *Transmission of Water and Fog.*—The selective scattering and consequent selective absorption of the atmosphere is well known and is illustrated in Fig. 13. The fine particles of dust and even molecules of gas are responsible for scattering the rays of shorter

wave-length more than those of longer wave-length. For this reason the setting sun is red; a cloud of smoke is blue, and the shadow of a puff of smoke is brownish. That this selectivity is dependent upon the size of the particles is also apparent. For example, smoke from the tip of a cigar is more bluish than that emanating from the moist end. In the latter case moisture has condensed around the carbon nuclei and these larger particles do not scatter light so selectively.

It is also known that water appears various tints of blue and blue-green when it is of great depth and purity. This is especially noticeable when flying over bodies of water although the effect of the color of the bottom and of the suspended matter washed from the shore must be separated from that of the water alone. Ordinary observations indicate that water selectively transmits rays in the green region; that is, rays of wave-lengths near the ends of the visible spectrum are transmitted less freely than those near the middle or especially in the green region — between 0.5μ and 0.6μ. This seems to have been fairly well established by experiment.

Recently Utterback [14] made some determinations of the passage of various colored lights, obtained by means of filters, through artificial fogs produced by expanding saturated air. His results indicate that his fogs were most transparent to light rays of wave-lengths from 0.53μ to 0.59μ. The transparency decreased rapidly toward the red but not so rapidly toward the blue end of the spectrum. Abbott [15] obtained similar results for water-vapor when there were dust particles in the air.

Bertel using a 'submarine' spectrograph photographed the visible spectrum of the light reaching various depths. His results show the visible spectrum to be

rapidly narrowed. The red rays being totally absorbed at depths of 5 to 10 meters; the orange at 20 meters; and the yellow at 100 meters. In the other end of the spectrum little selective absorption appears to take place until a depth of 30 meters is reached. At 1700 meters no light has been detected by any investigator. The range of the spectrograms obtained at various depths are presented in Table XXXIII.

TABLE XXXIII

Depths in meters	Range of wave-lengths
2	303$\mu\mu$ to 700$\mu\mu$
10	303 618
20	305 588
30	310 577
40	322 588
50	338 561
60	346 556
70	350 550
80	355 547
90	357 545
100	360 543
200	379 513
300	392 500
400	398 498

Many factors can influence the results obtained so that there is bound to be disagreement. However, water appears to have a definite selective transmission for light of a hue in the neighborhood of green.

110. *Color-temperature of Illuminants.*—The various colorimeters and the spectrophotometer have been used for the purpose of comparing illuminants and of representing their spectral characteristics respectively. Another method is to compare the integral color of an illuminant (at normal operation of the lamp) with the color of a 'black-body' radiator and rating the former in terms of the temperature of the latter when a color-

match (approximate in some cases) obtains. In Table XXXIV the results obtained by Hyde and Forsythe [16] are presented in terms of absolute temperatures (Kelvin scale). These values are termed 'color temperatures.' From these data and those on the black-body brightness-temperatures, the mean brightness of each light-source may be computed.

TABLE XXXIV

Gas flame, fish-tail (coal and water-gas)	1870 deg. K.
Hefner	1875
Pentane, 10 c. p. standard	1914
Candle, paraffin	1920
Candle, sperm	1925
Kerosene, cylindrical wick	1915
Kerosene, flat wick	2045
Acetylene, as a whole	2368
Acetylene, one spot	2448
Nernst glower, 2.3 w. p. h. c.	2388
Carbon filament, 4.0 w. p. h. c.	2070
Treated carbon filament, 3.1 w. p. h. c.	2153
Metallized carbon filament, 2.5 w. p. h. c.	2183
Osmium filament, 2.0 w. p. h. c.	2176
Tantalum filament, 2.0 w. p. h. c.	2249
Tungsten filament, 1.25 w. p. h. c.	2385
Tungsten filament, 0.9 w. p. h. c.	2543
Tungsten filament (gas-filled), 0.5 w. p. h. c.	2900 (approx.)

Kingsbury [17] using some of the foregoing values as reference points has made measurements of the color-temperature of commercial gas-burners obtaining values from 1940 to 2118 deg. K. As is to be expected, the color-temperature of a flame is within certain limits dependent upon its shape, size, and position and upon the composition of the gas. This method of rating illuminants yields valuable results.

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